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Parametric Equations for Estimating Aircraft Airframe Costs

Joseph P. Large, Harry G. Campbell and David Cates

A Report prepared for

ASSISTANT SECRETARY OF DEFENSE
(PROGRAM ANALYSIS AND EVALUATION)

Rand
SANTA MONICA, CA. 90406

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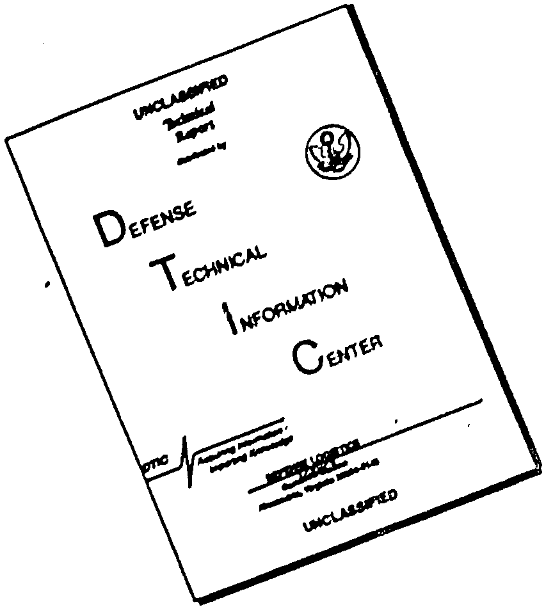

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PREFACE

This study was sponsored by the Office of the Assistant Secretary of Defense (Program Analysis and Evaluation) as part of a research program focused on improved methods of estimating the development, procurement, and operating costs of new weapon systems. The purpose of the study was to derive equations for estimating the acquisition cost of aircraft airframes. Such equations are intended primarily for use in long-range planning, not for contract negotiation or financial management.

This report was first distributed in May 1975. In the present printing, dated February 1976, the author has supplied supplementary material (Appendix C) illustrating how equations that appear to be comparable on the basis of statistical measurements can give widely different estimates of cost. The report should be useful to persons concerned with the selection, procurement, and production of military aircraft.

SUMMARY

Studies pertaining to the selection and acquisition of military aircraft generally begin with little more than a statement of the anticipated weight and the desired performance of a proposed aircraft. Even at that point, however, cost is an important consideration, and cost-estimating techniques must be devised that require only the available information, i.e., estimates of a limited number of physical and performance characteristics. This report presents generalized equations for estimating development and production costs of aircraft airframes on the basis of such characteristics as aircraft weight and speed. It provides separate equations for the following cost elements: engineering, tooling, nonrecurring manufacturing labor, recurring manufacturing labor, nonrecurring manufacturing material, recurring manufacturing material, flight-test operations, and quality control. It also provides equations for estimating total program cost and prototype development cost.

The estimating relationships are expressed in the form of exponential equations derived by multiple-regression techniques. Costs or man-hours are related to aircraft characteristics and quantity. In earlier Rand work[1,2] it was found that the characteristics that best explain variations in cost among airframes are airframe unit weight and maximum speed. A determined effort was made in the present study to find additional characteristics that would make an estimating model more flexible and hence better able to deal with characteristics peculiar to individual aircraft. That effort was not productive. The variations in cost that are not explained by weight and speed are not explained by any other objective parameters tested.

The equations presented here were derived from cost data on 25 military aircraft with first-flight dates from 1953 to 1970. (The

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[1] Levenson, G. S., and S. M. Barro, *Cost-Estimating Relationships for Aircraft Airframes*, The Rand Corporation, RM-4845-PR, February 1966.

[2] Levenson, G. S., et al., *Cost-Estimating Relationships for Aircraft Airframes*, The Rand Corporation, R-761-PR, December 1971.

earlier work included aircraft developed as far back as 1946.) The aircraft in the sample have airframe unit weights ranging from 5,000 to 279,000 lb and maximum speeds ranging from 300 to better than 1300 kn. Cost data were obtained directly from the airframe contractors whose aircraft appear in the sample and from standard Department of Defense references such as the Cost Information Report (now the Contractor Cost Data Reporting System).

The report explains the derivation of each of the estimating equations and describes the treatment of the data, the fitting of regression equations, and the selection of preferred equations. Other equations with additional explanatory variables are included where the statistical basis for choosing one equation over another is not strong. A detailed numerical example is included which applies the preferred equations and compares the results to those obtained using several sets of alternative equations.

ACKNOWLEDGMENTS

The authors wish to express their appreciation for the cooperation of the following major airframe companies: Boeing Aerospace Company, Fairchild Republic Company, General Dynamics Corporation, Grumman Aerospace Corporation, LTV Aerospace Corporation, Lockheed-California Company, Lockheed-Georgia Company, McDonnell-Douglas Corporation, Northrop Corporation, and Rockwell-International Corporation. Their willingness to provide data made the analyses described here possible. Within Rand technical assistance on engineering matters was provided by G. K. Smith and T. F. Kirkwood. Smith also acted as technical reviewer along with B. D. Bradley and D. Dreyfuss, and their comments were particularly helpful. H. E. Boren, Jr., K. Hoffmayer, and F. Kontrovich assisted with data preparation.

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I. INTRODUCTION

For many years estimates of aircraft airframe cost were based mainly on weight. The ARCO factor, for example (which took its name from the World War II Aircraft Resources Control Office), stipulated that manufacturing hours per pound of airframe could be estimated solely on the basis of airframe weight and production quantity. For a given quantity all aircraft were estimated from the same curve.

In the years since then estimators have been searching for other aircraft characteristics that (1) will, in combination with weight, provide consistently accurate estimates, (2) are logically related to cost, and (3) can easily be determined prior to actual design and development. The third requirement has led to use of characteristics such as speed, wetted area, and aspect ratio, rather than those that require more detailed knowledge such as number of engineering drawings or number of parts. A model published by Rand in 1966 showed that weight and speed were the only two explanatory variables that met the three criteria cited.[1] The model produced estimates that were found useful both by government and by industry, but the feeling lingered that it should be possible to achieve greater accuracy by including new and different variables.

Other companies, looking at ostensibly the same data, had developed models using additional variables. Planning Research Corporation, for example, found time to be an important variable for material costs.[2] Consequently, it was felt that a revised model could perhaps be more flexible, more responsive to program variations such as type of development program and development schedule. Also, after several years the addition of new aircraft to the U.S. inventory meant that the sample size could be increased and the enlarged sample would be more representative of aircraft likely to be developed in the future.

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[1] Levenson, G. S., and S. M Barro, *Cost-Estimating Relationships for Aircraft Airframes*, The Rand Corporation, RM-4845-PR, February 1966.

[2] *Methods of Estimating Fixed-Wing Airframe Costs*, Vol. I (Revised), PRC-547A, April 1967.

A revised model was published by Rand in 1971.[3] Several aircraft were added to the data base, a method for distinguishing between prototype and full development programs was added, and the procedures followed in developing the model were less judgmental. Users pointed out almost immediately, however, that the model suffered from what were believed to be shortcomings in the earlier version: (1) the only two major explanatory variables were weight and speed; (2) all aircraft were lumped together rather than treated as classes (e.g., fighters, bombers, etc.); and (3) no provision was made for taking into account changes in airframe structural materials and manufacturing methods. Consequently, when information on several new aircraft became available and it seemed desirable to update the data base, OSD (PA&E)[4] agreed to sponsor a research effort to produce a new estimating model and in the process deal explicitly with the questions raised earlier.

The study plan called for:

1. Review of airframe data in the Rand files to ensure accuracy and consistency of definition and acquisition data on new aircraft.
2. Consideration of additional explanatory variables that would make the model better able to deal with characteristics peculiar to individual aircraft, e.g., variable-geometry wing, oversize fuselage.
3. Examination of the cost impact of major changes in manufacturing technology over time and of the use of different structural materials.

Reviewing and expanding the data base turned out to be more of a job than was anticipated. Data had been collected over a period of years from a variety of sources, and to ensure internal consistency it was necessary to obtain additional cost details from airframe contractors.

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[3] Levenson, G. S., et al., *Cost-Estimating Relationships for Aircraft Airframes*, The Rand Corporation, R-761-PR, December 1971.

[4] The Office of the Assistant Secretary of Defense (Program Analysis and Evaluation).

Our goal was to obtain total contract cost for every contract of interest (i.e., out through the first few hundred aircraft) for over 30 military aircraft. In the time available it was not possible to resolve all the questions concerning data, but we believe our data sample is far more complete, comparable, and accurate than those used in previous analyses.

Our search for other explanatory variables that would improve the accuracy of estimates was less fruitful than we had hoped. The variations in cost that are not explained by weight and speed are not explained by any other objective indexes that we could find. For several of the cost elements, use of a dummy variable to distinguish cargo aircraft from other types proved beneficial. None of the other 20 or so variables considered, however, satisfied the criteria for inclusion.

It was necessary to examine the cost implications of major changes in airframe manufacturing technology and structural materials because the data sample consists largely of aluminum aircraft. The shift to other materials such as steel, titanium, and composites raises a question about the value of equations derived from that sample for estimating the cost of future aircraft. Titanium is much more expensive than aluminum and is more difficult to fabricate. The fasteners used to join titanium structural parts are many times more expensive on a per-unit basis than those customarily used in airframe assembly. On the other hand, adoption of a "unitized design concept" by some producers has reduced the number of parts and fasteners required. Thus the increase in fabrication man-hours may be offset by a decrease in assembly man-hours, and the shift would presumably result in a flattening of the cost-quantity curve. Statistical analysis does suggest a trend toward higher material costs and reduced manufacturing man-hours, and we discuss some of the qualitative considerations involved later in this report.

The estimating model developed is similar to previous Rand models in that it allows estimates to be made of individual cost elements (except in the case of prototype programs). An additional feature is that it allows estimates to be made of total program cost with no separation into cost elements. Several contractors suggested that more

accurate estimates could be achieved by estimating at the total program level, and a report on aircraft estimating prepared for the U.S. Navy makes a similar recommendation.[5] Our conclusion is that the results obtained from the two methods are comparable; we cannot say that either method gives consistently better estimates.

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[5]Noah, J. W., et al., *Estimating Aircraft Acquisition Costs by Parametric Methods*, J. Watson Noah Associates, Inc., FR-103-USN (abridged), September 1973.

II. RESEARCH PROCEDURE

DATA ACQUISITION AND REVIEW

The cost data used in this study were obtained from both government and industry, and within the time available every effort was made to ensure that the data were complete and comparable. Our goal was to obtain total contract cost for every contract of interest (i.e., out through the first few hundred aircraft) and to break that cost down into all the elements shown on the worksheet in Fig. 1. That amount of detail was not available for some of the older aircraft in the sample, but with the generous cooperation of major airframe contractors enough data were obtained to make sure that most costs are included and properly classified. The sample consists of the following aircraft:

A-3	C-133	F-86D
A-4	KC-135	F-89
A-5	C-141	F-100
A-6	F3D	F-102
A-7	F-3	F-104
B-47	F-6	F-105
B-52	F-4	F-106
B-58	F-14	F-111
RB-66	F-84A	T-38
C-5	F-86A	T-39
C-130		

Before the final analyses were made, all aircraft with first flight dates prior to 1952 (i.e., the B-47, F3D, F-84A, F-86A, F-86D, and F-89) were deleted from the sample, partially because of problems with the data and partially because development and production experience on aircraft that old does not appear to be a reliable guide to the future.

A basic question when dealing with data recorded by so many different contractors over so many years is whether to use actual costs or normalized costs. Actual costs may reflect problems that are irrelevant to the task of developing and producing an aircraft. A severe labor shortage, for example, may cause a contractor to hire unqualified

Model ______ Qty. ______ Del. Rate/Mo. ______ Contract No. ______ Type ______ Total Cost ($000) ______ Fee or Profit ______ Total ______

	Engineering					Tooling					Manufacturing						Quality Control				Total	
	Hrs	$	Ovhd	Matl	ODC	Hrs	$	Ovhd	Matl	ODC	Hrs	$	Ovhd	Matl	Pur Eq	ODC	Hrs	$	Ovhd	ODC	Hrs	$
Basic airframe Nonrecurring Recurring																						
Flight test (nonrecurring)																						
Mockups (nonrecurring)																						
Wind tunnel (nonrecurring)																						
Static-fatigue (nonrecurring)																						
Other test (nonrecurring)																						
System engineering Nonrecurring Recurring																						
Data (nonrecurring)																						
AGE Nonrecurring Recurring																						
Training Nonrecurring Recurring																						
Spares (recurring)																						
Retrofit (recurring)																						
Other Nonrecurring Recurring																						
G & A Nonrecurring Recurring																						
Total nonrecurring Total recurring																						
TOTAL																						

Fig. 1—Airframe cost-data worksheet

workers, with the result that manufacturing man-hours are higher than they would be under normal conditions. In anticipating a high production rate a contractor may expend many more tooling hours than can be justified by the production rates achieved. Engineering changes and modifications are a normal part of every program, but extensive changes due to customer decisions are not. Also, contractors speak of the effect of schedule changes. On one program the planned delivery schedule of one lot was accelerated by 6 months; on a later lot it was stretched out by 14 months. Such changes have a disruptive effect that can cause a temporary increase in manufacturing man-hours.

One point of view is that such problems are a normal part of the business of developing and producing military aircraft. An allowance for the cost implications of such problems must be made or an estimating model will consistently underestimate cost. The opposite view is that a contractor estimates the cost of building a certain aircraft in a certain way and at a certain rate, and thus the government should observe the same ground rules in reviewing his estimate--even though both parties know that design changes and schedule changes will occur and cause cost increases.

We have chosen to follow a middle course: In general, contractor data are used unchanged, but where a model change (e.g., the change from an A model to a B model) has demonstrably caused an increase in man-hours or costs, we have adjusted the data to eliminate that effect. Also, on the specific advice of contractors we have adjusted hours in a very few cases to what are believed to be more reasonable numbers. Our goal was to begin the analysis with a data base that is representative of the costs to be expected in a program with its fair share of problems but with no major design changes.

Achieving a perfectly consistent data base when the data have been compiled by so many different contractors is probably impossible because accounting practices differ so greatly among companies. The greatest source of potential error is in the treatment of off-site costs, e.g., purchased labor, vendor tooling, subcontracts, and outside production. Such costs sometimes turn up in contractor reports as *manufacturing material* or *other direct charges*. They can be identified only by an examination of contractor records, and then, along with

all other off-site costs, they must be converted into equivalent on-site labor hours and material costs. Unless we had information to the contrary we assumed that the subcontractor supplied any necessary material, and total subcontract value was reduced by an amount consistent with the in-plant manufacturing and material dollar distribution. The remaining amount was divided by a composite dollar rate calculated from the in-plant wage, overhead, and general and administrative rate plus an assumed profit for the contractor.

Requirements

Constructing an estimating model would be greatly simplified if the only requirement were to estimate total program cost or total development and total production costs. For long-range planning studies, estimates at such aggregated levels may suffice, but they are of little use in understanding why a new program is estimated to cost a certain amount. An analyst often wants to be able to compare major cost elements with their counterparts in previous programs to determine whether they seem reasonable and to make adjustments wherever indicated by special characteristics of the proposed aircraft.

For some purposes, then, it is essential to estimate at the major-cost-element level. In addition, it is desirable to distinguish between nonrecurring and recurring costs. Conceptually, the distinction is simple: Recurring costs are a function of the number of aircraft produced; nonrecurring costs are one-time expenditures. In practice, however, the distinction is more difficult because contractors may not keep track of costs in that way. Some accounts, such as mockups, wind tunnel, and static test, are clearly nonrecurring; and others, such as manufacturing material for production aircraft, are clearly recurring. Engineering and tooling hours are not so easily classified, and contractors appear to have somewhat different views on how to make the separation. For the older aircraft in the sample the separation is arbitrary because records were not kept that way. After-the-fact determinations are always open to question, and attempting to deal with nonrecurring and recurring costs separately introduces a certain amount of error into the data. Consequently, we did not attempt to

distinguish between nonrecurring and recurring costs where the distinction seemed unwarranted.

However, this does not mean that development and production costs cannot be separated. Assuming an aircraft program consisting of 20 test aircraft and 250 production aircraft, and using the cost elements for which estimating equations are derived, development and production costs would consist of the following:

Development Costs	Production Costs
Engineering for aircraft 1-20	Engineering for aircraft 21-250
Tooling for aircraft 1-20	Tooling for aircraft 21-250
Nonrecurring manufacturing labor	Recurring manufacturing labor for aircraft 21-250
Recurring manufacturing labor for aircraft 1-20	Recurring manufacturing materials for aircraft 21-250
Nonrecurring manufacturing materials	
Recurring manufacturing materials for aircraft 1-20	
Flight test	

Appendix A presents an illustrative example that shows in some detail how this may be done. The example also shows the relative importance of each cost element for a hypothetical military aircraft.

Dealing with cost elements separately may result in errors because possible complementaries between some of the elements are not taken into account. (Heavy investment in tooling should reduce manufacturing labor hours; extra care in initial engineering should reduce the number of changes later on; etc.) In addition, personnel at several airframe companies stated that in their experience a highly aggregated estimating model has been more accurate than detailed models. On the basis of that advice we derived equations for total program cost in addition to the equations for individual cost elements.

A second requirement was that the inputs, i.e., the information to be supplied by the estimator, be readily available. Aircraft characteristics such as weight, speed, aspect ratio, and ceiling can be specified long before engineering development begins, whereas more detailed information cannot be. Admittedly, characteristics do change.

Weight generally increases and speed sometimes decreases, so informed judgment concerning the validity of early estimates is important.

Estimates involving time are seldom reliable. If date of first flight or first production aircraft is a required input, early estimates can be off by several years. Length of development program and length of production program are even less likely to be estimated accurately; hence we have avoided these items. Subjective factors such as technological advance are also questionable because a priori judgments are often different from ex post facto judgments. We did consider them, however.

A third requirement was that the model distinguish between prototype development programs and full development programs. In the former, a small number of aircraft, usually less than 4, are built with no commitment to further production--no production planning, limited tooling, and limited systems development. The cost of a prototype program for the first few aircraft is substantially lower because many costs are deferred until a decision to produce for inventory is made. Total program cost is assumed to be the same for both approaches, but the time-phasing of cost is different. For planning and budgeting, that difference can be important.

Aircraft Groupings

Previous Rand models have not distinguished among types of aircraft; bombers, fighters, cargo aircraft, etc., have all been estimated by the same equations. Despite the intuitive appeal of stratifying the sample in that way, we have not done so for the following reasons. First, when the data were plotted as in Fig. 2, no natural boundaries appeared. Trainers are mixed with fighters, fighters with bombers, and bombers with cargo aircraft. That is not surprising in view of the fact that the B-58 and the F-111 are very similar in both weight and speed, and the T-38 is as large as some fighters and faster than many.

Second, the sample size for individual aircraft types was too small to be representative except in the case of fighters. However, because of the general belief that stratification of the sample into

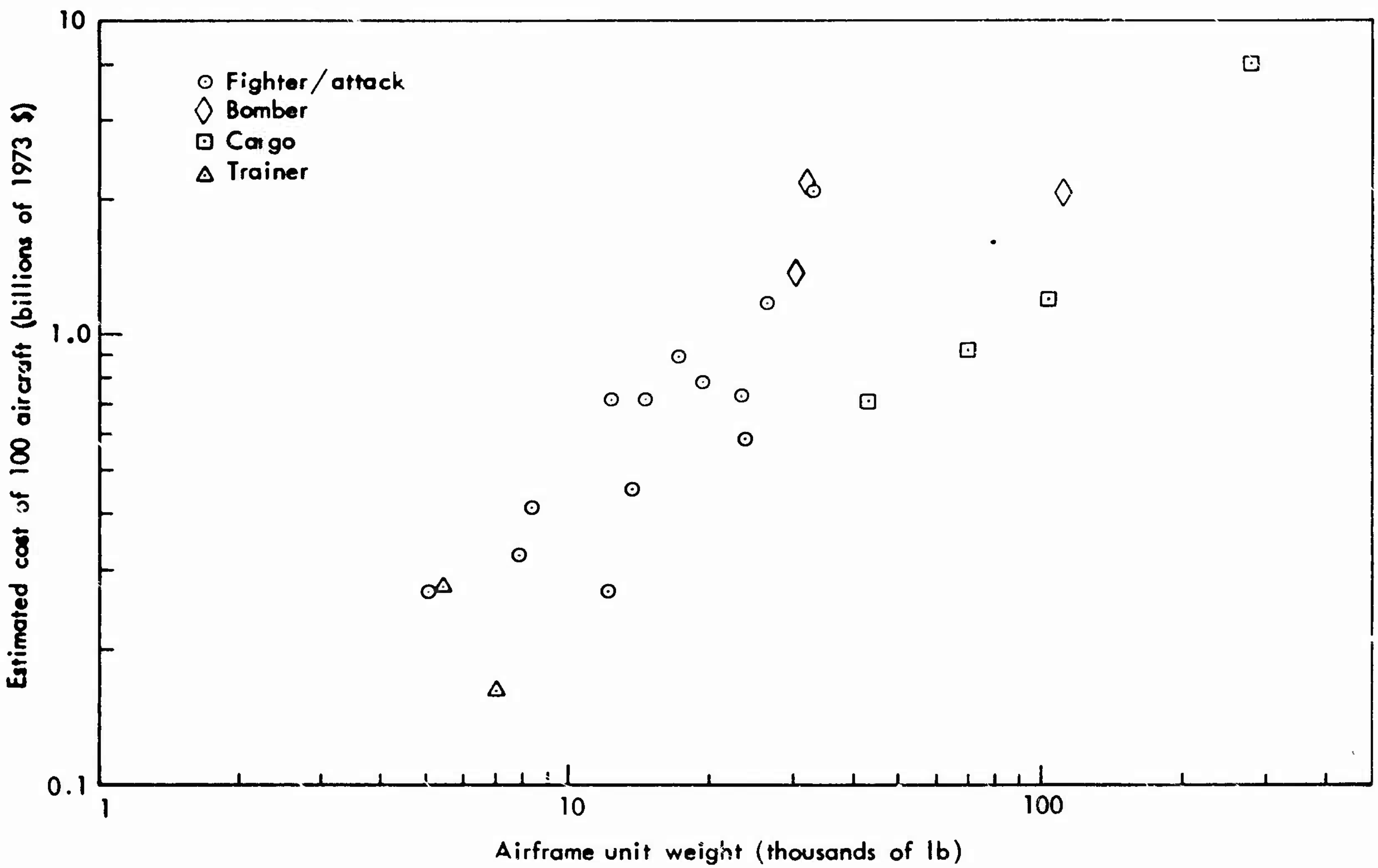

Fig. 2 — Estimated total cost of 100 aircraft versus airframe unit weight

more homogeneous groupings would result in improved estimating equations, we explored a number of possible groupings. In the course of the study aircraft were stratified by type (fighter, bomber, cargo), age, speed regime, weight, weight and speed, and structure design load factor.

Our conclusion is that the total sample is still too small and probably always will be, because at some point it becomes clear that experience with old aircraft is no longer relevant. Using a small sample of homogeneous aircraft is a good idea if the next aircraft is going to be very much like those in the sample. If, as is usually the case, the new aircraft will be substantially different, it is better to have a larger group of more diverse aircraft as a data sample.

Explanatory Variables

Estimators are continuously searching for a combination of aircraft characteristics that will provide consistently reliable estimates and be logically related to cost. Weight is a logical variable because it is an index of size, and all other things being equal a large aircraft should cost more than a small one. Apart from weight, however, no other variable is universally accepted. Previous Rand studies have found speed to be a useful variable, but other organizations have found it to be of no significance. In this study all the characteristics below were considered:

- Weight
- Speed
- Ceiling
- Climb rate
- Range factor
- Thrust-to-weight ratio
- Wing loading
- Aspect ratio
- Static thrust
- Lift-to-drag ratio
- Load factor
- Wetted area
- Ratio of gross takeoff weight to airframe unit weight
- Wing area
- Empty weight minus structure weight
- Ratio of wetted area to stress design weight
- Ratio of wetted area to wing area

The values of these characteristics are shown in Table 1.

Table 1

AIRCRAFT CHARACTERISTICS

Aircraft	Airframe Unit Weight (lb) (Q=100)	Speed (kn)	Test A/C	First Flight	Ceiling (ft)	Climb Rate (ft/min)	Range Factor	Wing Load (lb/ft^2)	Wing Area (ft^2)	Aspect Ratio	Wet Area (ft^2)	Static Thrust (lb)	L/D	Load Factor
A-3	23,931	556	5	9/53	40,900	5,050	---	77	779	6.8	3,899	20,000	13.2	5.00
A-4	5,072	578	9	8/54	40,800	8,400	---	61	260	2.9	1,144	7,000	11.0	10.50
A-5	23,499	1,147	11	6/58	48,400	27,900	---	74	254	3.7	---	34,000	13.2	11.00
A-6	17,150	563	8	4/60	---	---	---	---	528	5.3	---	---	---	---
A-7	11,621	595	7	9/65	37,200	8,580	---	76	375	4.0	1,690	14,250	13.2	10.50
B-52	112,672	551	13	6/54	43,900	5,120	---	73	4,000	8.6	---	96,800	21.1	3.00
B-58	32,686	1,147	30	11/57	63,000	17,830	---	54	1,542	2.1	---	41,200	11.7	3.00
RB-66	30,496	548	14	2/54	39,400	5,000	---	74	780	6.8	---	20,400	14.8	4.80
C-5	279,145	496	10	6/68	44,000	5,160	---	62	6,200	15.	30,800	163,220	17.5	3.75
C-130	43,446	326	9	4/55	35,850	3,900	---	43	1,746	10.	7,590	3,000	18.8	3.75
C-133	96,312	309	10	4/56	32,000	3,400	---	53	2,673	12.	13,150	6,000	17.5	3.75
KC-135	70,253	527	15	1/57	48,500	5,900	---	50	2,433	7.1	10,770	55,000	19.0	3.75
C-141	104,322	496	5	8/63	46,450	7,270	---	53	3,228	7.9	14,100	84,000	16.2	3.75
F-3	13,898	620	18	6/53	46,900	14,700	4,480	54	519	2.4	1,750	14,470	12.1	11.25
F-4	17,220	1,220	23	3/61	56,700	46,500	4,200	72	530	2.8	2,145	26,700	10.7	12.75
F-6(F4D)	8,737	628	13	6/54	54,200	20,200	3,820	35	557	2.0	1,500	15,700	10.0	9.50
F-14	26,500	^{a}	20	12/70	^{a}	^{a}	^{a}	86	565	7.3	---	40,000	14.6	9.75
F-100	12,118	713	13	10/53	52,500	25,700	4,820	60	385	3.9	1,509	11,700	11.9	11.00
F-102	12,304	677	42	7/55	51,800	18,700	5,390	38	662	2.2	2,170	14,450	11.3	10.50
F-104	7,963	1,150	19	2/56	58,600	51,500	4,500	80	196	2.4	1,078	11,000	10.2	11.00
F-105	19,301	1,195	15	5/56	50,200	38,300	5,200	79	385	3.2	---	24,000	11.1	13.00
F-106	14,620	1,153	42	12/56	53,700	34,500	6,230	43	695	2.2	2,236	18,450	12.2	10.50
F-111	33,150	1,262	18	4/67	55,500	12,600	8,250	128	525	7.6	2,580	36,000	15.5	11.00
T-38	5,376	750	14	1/59	52,000	28,500	---	62	170	3.8	---	5,360	12.8	11.00
T-39	7,027	468	4	5/60	37,500	4,270	---	44	342	5.8	---	6,000	12.8	11.00

^{a}Deleted because of security restrictions.

We have a mixed bag of reasons for choosing the parameters listed. Some have been shown in previous work at Rand or elsewhere to have predictive value. Others were included at the suggestion of persons in the airframe industry. A third group represents a conscious attempt to explain cost on the basis of assumptions about how aircraft are constructed. For example, the ratio gross takeoff weight to airframe unit weight and the value empty weight minus structure weight both reflect things put into an aircraft other than structure (engines, equipment, etc.); we included them on the assumption that installing lots of equipment might increase assembly cost. The ratio wetted area to wing area was an attempt to explain a previously noted correlation of cost with aerodynamic lift-to-drag ratio. The thought was that wings were cheaper to assemble than fuselage; hence aircraft with higher ratios of wing area to fuselage area (i.e., higher lift-to-drag ratios) should be less costly.

Unfortunately, aircraft characteristics alone cannot explain the variability in program costs. Schedule, management, funding, state-of-the-art advance, availability of labor, investment in capital tools--all these elements affect cost but cannot be captured in a simple model. A parametric cost model based on data from a wide assortment of programs is not sensitive to small changes, and it assumes that every program will have its fair share of technical, programming, and funding problems. Only when an explanatory variable has a consistent and perceptible influence in a variety of types of programs should it be included in a model.

For example, one of the variables most commonly suggested is time. Aircraft have changed over time in ways that are not reflected by weight or speed. They carry more avionics equipment, are fabricated by different machines, have more complex shapes and closer tolerances. It has often been conjectured that the effects of these changes could be captured by including a measure of time in the analyses, so flight date of first production aircraft was considered as a variable.

Some measure of state-of-the-art advance appeals to the intuition as a way of explaining why some programs are so much more costly than others. Such measures based on physical and performance characteristics

have been developed for aircraft turbine engines, but nothing comparable exists for airframes. We considered the use of a subjective assessment of program difficulty and concluded that the idea of a difficulty index has merit if it can be quantified properly. Our effort here was purely exploratory, however, and did not result in an index sufficiently reliable to merit inclusion in a cost model.

Other possible influences examined were (1) contractor records (do any contractors consistently display over-average or under-average costs in any of the major cost elements?); (2) type of development program, i.e., prototype or early production; (3) aircraft peculiarities, e.g., oversize fuselage, variable-geometry wing, carrier-based versus land-based. In general our conclusion is that no consistent and predictable influence could be detected for such characteristics.

Emphasis on Man-Hours

We believe it is essential to work with man-hours rather than dollars whenever possible, for several reasons. First, adjustments for yearly price changes are not required. Adjusting costs over a period of 25 years to achieve constant dollars can introduce substantial discrepancies into the data. All price indexes are inexact, and for many specialized items of equipment there is no good, published price index. Another problem is that of identifying the years in which expenditures occur when the data show only total contract cost. Production and cash flow are normally spread out over a period of several years, and costs should be adjusted for each year separately to reduce errors to a minimum. When dealing in man-hours, such adjustments are unnecessary.

Second, for estimating purposes we are concerned with the labor required to develop and produce aircraft, not what that labor costs. Wage and overhead rates can differ greatly among contractors, and they can fluctuate from year to year within the same company for reasons quite independent of the inflationary trend. Estimating in dollars rather than hours means that real differences in requirements may be understated or overstated.

ANALYTICAL TECHNIQUES

The specific analytical techniques employed to deal with the various cost elements are described in the sections covering those elements. In general, we have relied on the technique of multiple-regression analysis. To obtain input values, we plotted cumulative total hours or dollars, adjusted for model changes, against cumulative aircraft quantity and drew lines between plot points. From those lines values were obtained for quantities 25, 50, 100, and 200. In some cases, lines were extrapolated along the established slope to obtain a value for a greater number of aircraft than were actually built; e.g., only 81 C-5As were produced, but we extrapolated the cost-quantity curve out to 200 aircraft to keep sample size constant for all quantities of aircraft.

The reason for examining cost at several quantities was to see if a segmented, rather than a linear, cost-quantity curve would fit the data better and provide better estimates for small quantities of aircraft. Our conclusion is that the curve is sufficiently linear from 25 aircraft onward so that nothing is gained by using a segmented curve. Major departures from a linear curve may occur, however, for small quantities of aircraft, i.e., less than 10. Prototype programs of 1 to 3 aircraft must be treated separately.

Initially, a stepwise least-squares procedure was used to determine which of the many explanatory variables considered were statistically significant. Most of the possible varibles were eliminated immediately because they seemed to have so little predictive value. The 4 or 5 remaining variables were then examined from the standpoint of logic. The question posed in each case was, Can a defensible hypothesis be constructed that would explain why cost should be influenced by this variable? Some of the variables fell by the wayside at that point, and we concluded that despite their deficiencies, airframe weight and speed are still the most dependable predictors of cost.

The multiple-regression computer program used calculates the usual statistical measures of fit--coefficient of correlation, coefficient of variation, F-value, etc. Rather than show only those that we regard

as most meaningful, we have had the complete computer printouts reproduced so that the reader can examine all the statistics. In general, in selecting preferred equations throughout this study we looked for a high coefficient of determination (R^2), a low mean absolute percentage of Y-deviations, and a level of significance for all independent variables of at least 90 percent.

The question as to whether the regressed power function or its regressed logarithmic form is more appropriate for a set of data depends on many factors including the error term associated with the data and what criterion is used for a good fit. One of the best tests for comparison is to examine the plot of Y-residuals versus calculated Y-values or for the logarithmic case the residuals of log (observed Y) versus log (calculated Y). The better model will show a more random, normal distribution of the Y-residuals about the zero-residual line. Moreover, for many of the statistics to be valid, the plot must show such a random distribution.

When both logarithmic and power regressions were made on the data, the plots obtained showed in most cases a better distribution of the residuals for the logarithmic form than for the power form. This is consistent with current belief at Rand that (1) the error distributions for cost data tend to be more constant over the range of data in the logarithms than in the actual (raw) values, and (2) the criterion of percentage (relative) errors is more appropriate than one of actual errors. (The logarithmic regression minimizes relative errors rather than actual errors as in the power regression.) As a result, a logarithmic model was used for all regressions.

III. ENGINEERING

Engineering refers both to engineering for the basic airframe and to the system engineering performed by the prime contractor. More specifically, it includes engineering for design studies and integration; for wind-tunnel models, drop model, mockups, and propulsion-system tests; for laboratory testing of components, subsystems, and static and fatigue articles; for preparation and maintenance of drawings and process and materials specifications; and for reliability. Engineering hours not directly attributable to the aircraft itself (those charged to ground handling equipment, spares, and training equipment) are not included. Engineering hours expended as part of the tool and production-planning function are included with the cost element *tooling* (see Sec. IV).

Our original intent was to estimate nonrecurring and recurring hours separately, but regression analyses of hours reported by contractors as "nonrecurring" indicated discrepancies in the data. Consequently, cumulative total engineering hours were plotted for each aircraft, and values were read off the curves at 25, 50, 100, and 200 aircraft. Those values were then regressed against possible explanatory variables. For the complete sample the best results were obtained using weight, maximum speed, and time (expressed as number of quarters after 1942 that first flight of a production aircraft occurred). The regression equation for cumulative total engineering hours for 100 units and some of the statistical properties of that equation are shown below[1] (the number under each independent variable is the level of significance of that variable):

$$E_{100} = .00081\underset{1.00}{(\mathrm{Wt})^{.67}}\underset{.99}{(\mathrm{Speed})^{.99}}\underset{.95}{(\mathrm{Time})^{.65}}$$

$$R^2 = .86$$

$$\mathrm{SEE}(\%) = +40, -29$$

$$F = 41$$

[1] Equations for 25, 50, and 200 units are not shown in the body of this report. They are included in Appendix B along with a more complete statement of the associated statistics for all equations.

where E_{100} = cumulative total engineering hours for 100 units (thousands)

Wt = airframe unit weight (lb)[2]

Speed = maximum speed (kn)

Time = quarters after 1942 that first flight of production aircraft occurred.

Time is not a completely satisfactory variable, for several reasons. It assumes that change is regular and is always in the same direction--every succeeding year brings an increase in engineering hours. As a description of a trend over the past 25 years, that assumption is irrefutable, but as a working hypothesis for the future, it is open to challenge--at least on philosophical grounds.

An alternative, of course, is to eliminate time as a variable. The results obtained by that means are shown below:

$$E_{100} = .0016\underset{1.00}{(Wt)^{.75}}\underset{1.00}{(Speed)^{1.17}}$$

$$R^2 = .83$$

$$SEE(\%) = +44, -31$$

$$F = 52$$

It will be noted that the statistics are not quite as good as in the previous equation and that speed has become more important. The increase in engineering hours over time is implicitly attributed to higher speeds--an assumption that may work well for fighter aircraft but would lead to an understatement of costs for an aircraft such as the C-5.

It seemed to us that an equation was needed that would not have the objectionable features of either of the two approaches described

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[2] Airframe unit weight is defined as empty weight minus the following: wheels, brakes, tires, and tubes; engines--main and auxiliary; rubber or nylon fuel cells; starters--main and auxiliary; propellers; auxiliary power-plant unit; instruments; batteries and electrical power supply and conversion; avionics group; turrets and power-operated mounts; air conditioning, anti-icing and pressurization units and fluids; cameras and optical viewfinders; trapped fuel and oil.

above. Visual inspection of the data led to an observation that we felt might be of use in deriving a better equation: It appeared that 1958 was something of a watershed year. Aircraft developed prior to that year tended to have substantially fewer engineering hours than those developed later. Two alternative procedures were used to determine whether that observation could be used to improve the estimating qualities of the equation. First, a dummy variable was added to distinguish between the two age groups without decreasing the size of the sample. Second, a sample consisting only of the following 9 post-1957 aircraft was examined: A-5, A-6, B-58, C-141, C-5, F-4, F-14, F-111, and T-38. Both procedures improved the statistics substantially, but of the two the small sample appeared to be preferable. The equation is shown below:

$$E_{100} = .023\underset{.99}{(\mathrm{Wt})^{.66}}\underset{.99}{(\mathrm{Speed})^{.96}}$$

$$R^2 = .90$$

$$\mathrm{SEE}(\%) = +30, -23$$

$$F = 26$$

Table 2 shows the Y-deviations (in percent) for recent aircraft for each of the three estimating models. Estimates for 5 aircraft are more accurate with the small sample, and the absolute mean of Y-deviations improved to 17 percent. Since it seems unlikely that aircraft development practices comparable to those prior to 1958 will be regenerated in the future, we believe the equations based on the small sample are preferable to the others.

The tables in Appendix B give equations for quantities of 25, 50, 100, and 200 airframes. To obtain values for other quantities one can:

1. Calculate the values at the two quantities closest to the desired quantity and interpolate or extrapolate as necessary.
2. Calculate the values at all four quantities and fit a curve to those four points.

Table 2

PERCENT Y-DEVIATIONS: CUMULATIVE ENGINEERING HOURS AT 25 UNITS

	Small Sample	Full Sample	
Aircraft	Weight, Speed	Weight, Speed, Time	Weight, Speed
A-5	-23	7	1
A-6	-1	24	38
B-58	-5	22	12
C-5	1	18	36
C-141	-39	-23	-2
F-4	-15	9	9
F-14	5	-13	18
F-111	20	14	31
T-38	18	42	52
Absolute mean	17	19	22

3. Assume a typical cost-quantity curve slope and pass a curve with that slope through the value at 200 units.

The third method would be used primarily for quantities greater than 200. It has the advantage of ensuring that aircraft weight and speed do not distort the slope of the curve away from the range normally expected. Table 3 shows that range. With one exception, it extends from 108 to 124 percent, and the most common slopes are from 111 to 114 percent. The mean slope (excluding the outlier at 133 percent) is 112.6 percent or, when stated as an exponent in mathematical terms, 0.181. A comparable value of .20 was obtained in the Levenson-Barro study[3] with a smaller sample that included no aircraft developed in the 1960s. In a subsequent study, Levenson and Timson obtained a slope of .183. Thus we have some confidence that the slope of the engineering-hour curve for a typical program should be about 113 percent.

[3]Op. cit., 1966.

Table 3

ENGINEERING COST-QUANTITY CURVE SLOPES[a]

Aircraft Type	Slope Exponent	Slope Percent	Aircraft Type	Slope Exponent	Slope Percent
Trainer	.117	108	Bomber	.188	114
Cargo	.128	109	Fighter	.188	114
Attack	.130	109	Cargo	.192	114
Fighter	.130	109	Bomber	.192	114
Attack	.140	110	Cargo	.194	114
Fighter	.145	111	Fighter	.201	115
Attack	.147	111	Cargo	.206	115
Cargo	.149	111	Attack	.218	116
Fighter	.156	111	Fighter	.245	119
Fighter	.167	112	Trainer	.306	124
Fighter	.167	112	Fighter	.306	124
Fighter	.171	113	Bomber	.409	133

[a]Log-linear cumulative total curves have been used throughout this study for ease of computation. Persons more accustomed to thinking in terms of cumulative average curves can convert cumulative total slope in percent to cumulative average slope simply by dividing by 2, e.g., a cumulative total slope of 114 percent is equivalent to a cumulative average slope of 57 percent.

IV. TOOLING

Tooling refers only to the tools designed for use on a particular program, i.e., assembly tools, dies, jigs, fixtures, work platforms, and test and checkout equipment. General-purpose tools such as milling machines, presses, routers, and lathes (except for the cutting instruments) are considered capital equipment. If such equipment is owned by the contractor (much of it is government-owned), an allowance for depreciation is included in the overhead account. *Tooling hours* include all effort expended in tool and production planning, design, fabrication, assembly, installation, modification, maintenance, and rework of tools, and programming and preparation of tapes for numerically controlled machines. Nonrecurring tooling refers to the initial set of tools and all duplicate tools produced to attain a specific rate of production.

Again, as in the case of engineering hours, the distinction between nonrecurring and recurring hours is more apparent than real. The problem is more difficult here because duplicate tools may be procured at any point in an aircraft's production run, and those nonrecurring hours may or may not be properly categorized. Those hours designated as nonrecurring by contractors are plotted against airframe unit weight in Fig. 3. The dispersion is so great that no useful estimating relationship could be developed.

By combining nonrecurring and recurring tooling hours and estimating cumulative total hours of various quantities, a reasonably good relationship was obtained using weight and speed as the only independent variables:

$$T_{100} = .47\underset{1.00}{(\mathrm{Wt})^{.64}}\underset{.98}{(\mathrm{Speed})^{.50}}$$

$$R^2 = .71$$

$$\mathrm{SEE}(\%) = +51, -34$$

$$F = 27$$

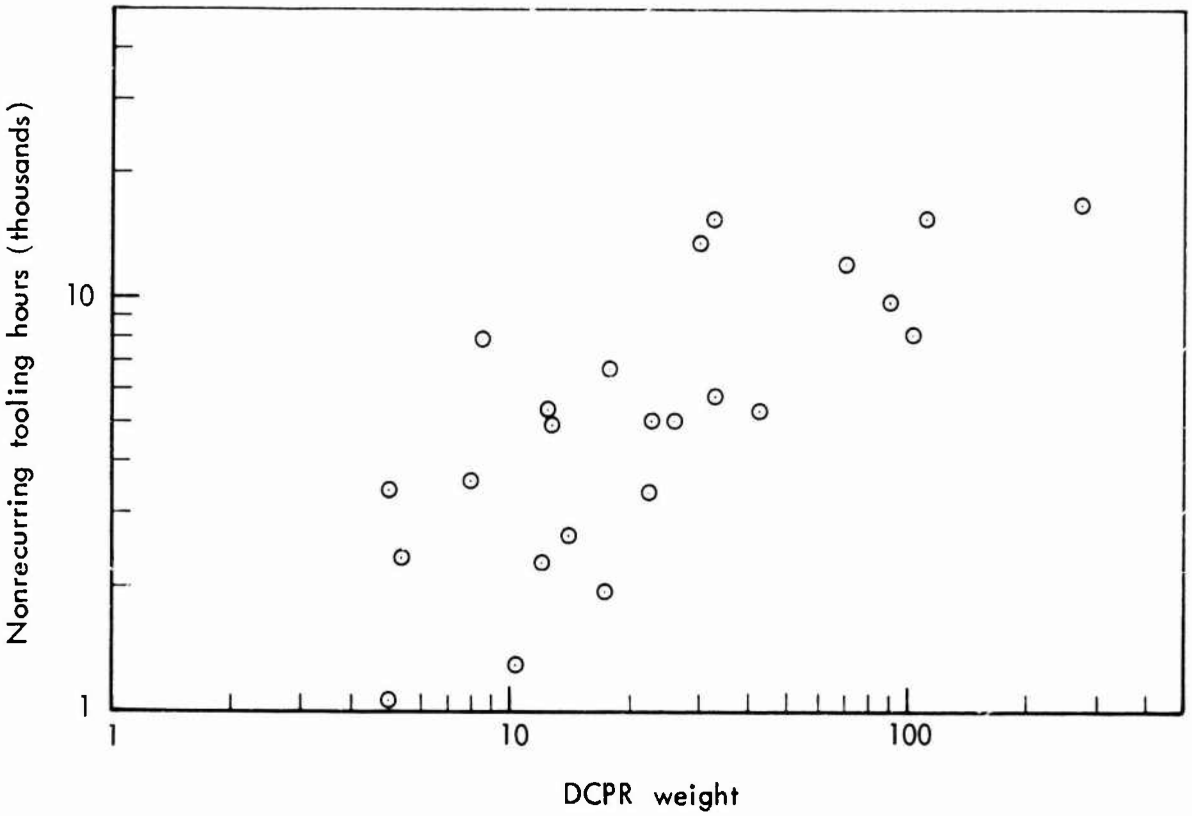

Fig. 3 — Contractor estimates of recurring tooling hours

where T_{100} = cumulative total tooling hours for 100 units (thousands)

Wt = airframe unit weight (lb)

Speed = maximum speed (kn).

A third independent variable--the ratio of gross takeoff weight to airframe unit weight--improved the estimating relationships slightly, but the problem of achieving a consistent definition of gross takeoff weight plus the fact that the parameter is not intuitively satisfying caused us to abandon that variable.[4] Previous Rand studies have found production rate to be a useful independent variable for estimating

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[4]Gross takeoff weight is affected by mission configurations that may vary widely for a given aircraft.

tooling hours, but we found that while it does improve the R^2 slightly, it does not reduce the residuals, and it is not significant statistically. Also, since production rate is difficult to predict very far in advance and is subject to changes, it is an undesirable variable to rely on.

The fact that production rate is not a useful variable is unfortunate, however, because rate does in fact affect tooling hours. The reasons why rate may not be statistically significant are discussed at length in an earlier Rand report.[5] In brief, it appears that rate affects tooling hours very differently for different programs depending on how rate is planned for and how it is achieved (e.g., by multishift operations versus more tools). Also, the input data lack precision, because while we know the rate at which aircraft were produced we may not know the planned rate, i.e., the rate for which tooling hours were expended. Thus it is not surprising that the regression equations show a poorer fit for tooling than for the other major cost elements.

The slope of the tooling curve is much less regular than that of the engineering curve, because nonrecurring tooling hours may be incurred after a sizable number of aircraft have been delivered. At some point a steady-state condition will be achieved, but that point will be much farther along for programs with a high production rate. Consequently, we do not recommend fitting a curve to values obtained at 25, 50, 100, and 200 aircraft and using that curve to estimate tooling hours for quantities greater than 200. A flatter and more representative curve will be obtained by using only the last two points (100 and 200 units).

As a check on the slopes obtained by plotting those points, Table 4 shows the slopes obtained after most nonrecurring hours have been incurred. The mean, 116 percent, is actually a little higher than previous studies would lead one to expect. For quantities greater than 200 where recurring tooling hours only are being incurred, a slope of 112 percent would be more typical.

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[5] Large, J. P., et al., *Production Rate and Production Cost*, The Rand Corporation, R-1609-PA&E, December 1974.

Table 4

TOOLING COST-QUANTITY CURVE SLOPES

Aircraft Type	Slope		Aircraft Type	Slope	
	Exponent	Percent		Exponent	Percent
Fighter	.098	107	Attack	.215	116
Bomber	.111	108	Fighter	.219	116
Trainer	.112	108	Cargo	.219	116
Cargo	.122	109	Bomber	.245	118
Cargo	.141	110	Attack	.246	119
Cargo	.149	111	Fighter	.257	120
Bomber	.160	112	Fighter	.261	120
Attack	.166	112	Attack	.266	120
Fighter	.182	113	Fighter	.296	123
Fighter	.192	114	Fighter	.342	127
Cargo	.193	114	Attack	.351	128
Trainer	.209	116	Fighter	.369	129
			Fighter	.387	129
Mean				.220	116

V. MANUFACTURING LABOR

Nonrecurring manufacturing labor is defined here to mean the man-hours expended to produce mockups, models, test parts, static test items, and other items of hardware--excluding complete flight-test aircraft--needed for airframe development. It does not include manufacturing hours incurred in support of the flight-test program.

An attempt was made to relate nonrecurring hours to weight, speed, and a number of other variables. The best results are shown below:

$$ML_{NR} = .00063 \underset{.99}{(Wt)^{.69}} \underset{.99}{(Speed)^{1.21}}$$

$$R^2 = .53$$

$$SEE(\%) = +106, -52$$

$$F = 12$$

where ML_{NR} = nonrecurring manufacturing man-hours (thousands)

Wt = airframe unit weight (lb)

Speed = maximum speed (kn).

Admittedly, the predictive qualities of this equation leave something to be desired, but none of the other variables examined improved the situation. It may be that the data are inconsistent or that the variability in nonrecurring hours is very high because of differences in the amount of hardware produced for test purposes. On some programs emphasis is placed on getting test aircraft into the air as quickly as possible, with less emphasis on ground test. On others, elaborate mockups are constructed, and the differences between programs do not appear to be directly related to physical or performance characteristics of the aircraft.

Recurring manufacturing labor is all the direct labor necessary to machine, process, fabricate, and assemble the major structure of an aircraft and to install purchased parts and equipment, engines,

avionics, and ordnance items, whether contractor-furnished or government-furnished. Recurring manufacturing man-hours include the labor component of off-site manufactured assemblies and effort on those parts which, because of their configuration or weight characteristics, are design-controlled for the basic aircraft. These parts normally represent significant proportions of airframe weight and of the manufacturing effort, and are included regardless of their method of acquisition. Such parts specifically include actuating hydraulic cylinders, radomes, canopies, ducts, passenger and crew seats, and fixed external tanks. Man-hours required to fabricate purchased parts and materials are excluded from this cost element.

Because manufacturing labor is the largest cost element, it was given more attention than the other cost elements in the hope of finding aircraft characteristics that could be logically related to manufacturing considerations and to cost. The results were little different from those of previous Rand studies: Weight and speed are dominant and no other aircraft characteristics are significant except one--lift-to-drag ratio. Since, as mentioned earlier, we were unable to support any hypothesis explaining why aircraft with high lift-to-drag ratios should require fewer man-hours, we concluded that the correlation was spurious.

One additional variable that does seem plausible and did improve the statistical properties of the equations slightly is time. The results with and without time are shown below:

$$ML_{100} = .79\underset{1.00}{(Wt)^{.85}}\underset{.99}{(Speed)^{.56}}\underset{.94}{(Time)^{-.53}}$$

$$R^2 = .87$$

$$SEE(\%) = +37, -27$$

$$F = 48$$

$$ML_{100} = .35\underset{1.00}{(Wt)^{.79}}\underset{.98}{(Speed)^{.42}}$$

$$R^2 = .85$$

$$SEE(\%) = +40, -29$$

$$F = 6[illegible]$$

where ML_{100} = recurring manufacturing man-hours (thousands)

Wt = airframe unit weight (lb)

Speed = maximum speed (kn)

Time = number of quarters after 1942 that first flight of a production aircraft occurred.

The statistical significance of time is interesting because it lends support to the hypothesis that new manufacturing procedures are reducing manufacturing man-hours. The equation for 100 aircraft implies that cumulative man-hours for 100 airframes decreased by about 20 percent between 1960 and 1970. That figure seems a little high. The evidence is persuasive that new methods *can* reduce labor hours per pound, but a survey of manufacturing procedures in three airframe companies suggests that an assumption of reduced manufacturing man-hours for future aircraft may not always be warranted. Fabrication hours increase where composite materials and aluminum and titanium machined parts are introduced, e.g., fabrication hours per pound are about 10 percent higher on the F-15 than on the F-4. Major assembly hours for the F-15, on the other hand, are down to 55 percent of those required for the F-4, primarily because of the use of larger parts. The net result is a 20 percent decrease in labor hours per pound at the 20th aircraft.

The shift of man-hours from assembly to fabrication means less opportunity for labor learning, hence a flatter learning curve. Reduction in cost at the 20th unit may be offset by increases in cost at the 200th unit. Historically, cumulative slopes have been as shown below in Table 5. No clear consensus exists for any one slope, but the mean is 154 percent, which equates to 77 percent on a cumulative average curve. If the equations with time as a variable are used to obtain manufacturing hours at 25, 50, 100, and 200 units and a curve is fitted to those points, the slope will be about 160 percent (80 percent on a cumulative average curve). The equations containing weight and speed only appear to give results closer to traditional values. The question of slope arises only for programs larger than 200 aircraft, and at that point cost-quantity effects are less important.

Table 5

CUMULATIVE RECURRING MANUFACTURING LABOR
COST-QUANTITY CURVE SLOPES

Aircraft Type	Slope		Aircraft Type	Slope	
	Exponent	Percent		Exponent	Percent
Attack	.490	140	Fighter	.616	153
Fighter	.516	143	Cargo	.633	155
Trainer	.528	144	Bomber	.638	156
Fighter	.530	144	Attack	.652	157
Fighter	.544	146	Fighter	.665	159
Bomber	.522	147	Bomber	.674	160
Trainer	.566	148	Fighter	.683	161
Cargo	.573	149	Fighter	.702	163
Cargo	.577	149	Attack	.711	164
Fighter	.581	150	Attack	.726	165
Cargo	.588	150	Cargo	.744	167
Attack	.592	151	Fighter	.864	182
Fighter	.602	152			
Mean				.622	154

VI. MANUFACTURING MATERIALS

Manufacturing materials include raw and semifabricated materials plus purchased parts (standard hardware items such as electrical fittings, valves, and hydraulic fixtures) used in the manufacture of the airframe. This category also includes purchased equipment, i.e., items such as actuators, motors, generators, landing gear, instrument , and hydraulic pumps, whether procured by the contractor or furnished by the government. Where such equipment is designed specifically for a particular aircraft, it is considered as subcontracted, not as purchased equipment.

Some of the purchased equipment on an aircraft is furnished to the contractor by the government. That government-furnished aircraft equipment (GFAE) typically includes landing gear, electrical equipment, and instruments. The cost is not included in contractor reports and must be sought out in government records for each aircraft. Since time did not permit a thorough search, the following procedure was adopted. Actual GFAE costs were used where available (on 10 aircraft). From those costs the equation below was derived and used to estimate GFAE costs for the remaining aircraft:

$$Y = 29.9\,X^{.38}$$

where Y = GFAE cost (thousands of 1973 \$) and X = airframe unit weight (thousands of lb). This procedure introduces a certain amount of error into the material costs, but it seemed preferable t omitting GFAE costs entirely.

Material costs must be adjusted for price-level changes over the years to make them comparable. Two indexes were used for that purpose--one for raw materials and purchased parts and another for purchased materials.[1]

[1] The procedures used to obtain the index numbers are described in H. G. Campbell, *Aerospace Price Indexes*, The Rand Corporation, R-568-PR, December 1970. The indexes in that report were updated to a base year of 1973 by E. S. Ojdana, Jr., of Rand.

Table 6 shows the index numbers used.

Table 6

MATERIAL PRICE CONVERSION FACTORS

Year	Airframe Materials	Purchased Equipment
1946	3.610	4.087
1947	3.406	3.856
1948	3.213	3.638
1949	3.031	3.432
1950	2.860	3.238
1951	2.805	3.176
1952	2.625	2.972
1953	2.480	2.808
1954	2.359	2.656
1955	2.224	2.506
1956	2.081	2.353
1957	1.970	2.226
1958	1.859	2.078
1959	1.793	1.981
1960	1.718	1.892
1961	1.672	1.833
1962	1.614	1.756
1963	1.579	1.696
1964	1.528	1.632
1965	1.479	1.568
1966	1.422	1.496
1967	1.359	1.422
1968	1.295	1.343
1969	1.208	1.249
1970	1.177	1.188
1971	1.137	1.138
1972	1.094	1.081
1973	1.000	1.000

Nonrecurring materials are those required to produce mockups, test parts, static test items, and other hardware items (excluding complete flight-test aircraft) needed for airframe development. The cost of nonrecurring materials for aircraft in the sample ranges from $544,000 to $80 million, and no combination of independent variables that we could devise explained a range of that magnitude. The most dependable results are given below:

$$MM_{NR} = .000024\underset{.99}{(Wt)^{.72}}\underset{.99}{(Speed)^{1.92}}$$

$$R^2 = .68$$
$$SEE(\%) = +94, -49$$
$$F = 23$$

where MM_{NR} = nonrecurring materials cost (thousands of 1973 \$)
Wt = airframe unit weight (lb)
Speed = maximum speed (kn).

As mentioned in Sec. V, airframe materials have been changing over time and costs can be expected to change as well. Titanium, stainless steel, composites, new types of fasteners, etc., are being used extensively in some new aircraft. However, because the cost of raw materials and minor purchased parts is a relatively small part of the total materials costs in an aluminum airframe--less than 25 percent--increases in costs of raw materials tend to be overlooked until they become substantial. In the F-14 and F-15 airframes, for example, approximately 25 percent of the airframe unit weight is titanium, and that is estimated to increase the total materials cost per pound by about 12 percent over that for previous fighters.

An estimating relationship relying on weight and speed only is unlikely to capture such cost increases. Use of a weight variable with no offsetting feature means that a decrease in weight shows up as a decrease in cost even though the opposite may be true. Some airframe contractors estimate in terms of a cost-weight, i.e., the weight of all titanium, steel, composites, etc., is converted into an equivalent number of pounds of aluminum and the latter used for estimating purposes. Such a procedure may be preferable but would violate our rule that estimating inputs be easily obtainable prior to detailed aircraft design. As an alternative we decided to see whether a time trend could be detected. The equations below show that when time is included as a third independent variable it is not as significant as one would hope for, but the results are slightly better than those obtained without it. The

coefficient implies that between 1975 and 1985 material costs will increase by about 12 percent or just slightly more than 1 percent per year. That does not seem unreasonable and does provide a hedge against increasing materials costs.

$$MM_{100} = \underset{1.00}{.050(Wt)^{.88}}\underset{.99}{(Speed)^{.87}}$$

$$R^2 = .86$$
$$SEE(\%) = +43, -30$$
$$F = 67$$

$$MM_{100} = \underset{1.00}{025(Wt)^{.83}}\underset{.99}{(Speed)^{.75}}\underset{.87}{(Time)^{.46}}$$

$$R^2 = .87$$
$$SEE(\%) = +42, -29$$
$$F = 49$$

where MM_{100} = manufacturing materials cost (thousands of 1973 $)
Wt = airframe unit weight (lb)
Speed = maximum speed (kn)
Time = number of quarters after 1942 that first flight of a production aircraft occurred.

Recurring materials cost observes the cost-quantity effect faithfully in all aircraft programs, but the range of calculated slopes in our sample is too wide to be completely credible. Price-level changes, purchasing patterns, different accounting procedures, or other causes appear to be affecting the slopes given in Table 7. Still, the mean slope is essentially the same as that obtained for a somewhat different sample of aircraft in the Levenson-Timson study, i.e., 171 percent versus 173 percent, or for a cumulative average curve, 85.5 percent versus 86.5 percent.

Table 7

MATERIALS COST-QUANTITY CURVE SLOPES

Aircraft Type	Slope		Aircraft Type	Slope	
	Exponent	Percent		Exponent	Percent
Fighter	.500	141	Fighter	.817	176
Fighter	.568	148	Cargo	.824	177
Attack	.652	157	Cargo	.825	177
Fighter	.654	157	Fighter	.834	178
Cargo	.663	158	Attack	.835	178
Bomber	.667	159	Fighter	.847	180
Bomber	.679	160	Trainer	.853	181
Trainer	.726	165	Cargo	.869	182
Cargo	.735	166	Fighter	.902	187
Attack	.735	166	Attack	.909	188
Fighter	.769	170	Attack	.911	188
Fighter	.800	174	Fighter	1.005	200
Bomber	.806	175			
Mean				.775	171

VII. FLIGHT TEST

Flight test includes all costs incurred by the contractor in the conduct of flight testing except production of the test aircraft. Engineering planning, data reduction, manufacturing support, instrumentation, all other materials, fuel and oil, pilot's pay, facilities, rental, and insurance costs are included. Flight-test costs incurred by the Air Force, Army, or Navy are excluded.

Flight test is treated as a separate cost element because it is generally kept as a separate account by contractors, and the costs should be relatively accurate. It is a composite of various types of labor and materials, all of which we have converted to 1973 dollars using the index shown in Table 8.

Table 8

AIRCRAFT LABOR INDEX

Year	Index	Year	Index	Year	Index
1950	3.130	1958	2.020	1966	1.518
1951	2.897	1959	1.921	1967	1.453
1952	2.711	1960	1.871	1968	1.389
1953	2.561	1961	1.824	1969	1.300
1954	2.438	1962	1.767	1970	1.216
1955	2.336	1963	1.719	1971	1.163
1956	2.233	1964	1.690	1972	1.070
1957	2.157	1965	1.610	1973	1.000

The independent variables found to be significant here, other than weight and speed, were the number of flight-test aircraft and a dummy variable to distinguish between cargo aircraft and all other types. The cost of instrumenting the test aircraft is an important portion of flight-test cost; thus, cost should increase as the number of aircraft increases. And cargo aircraft require less flight testing than fighters and bombers, so cargo-aircraft flight-test costs should lower. The estimating equation is given below:

$$FT = \underset{.99}{.13(Wt)^{.71}}\underset{.92}{(Speed)^{.59}}\underset{.99}{(N)^{.72}}\underset{.99}{(DV)^{-1.56}}$$

$R^2 = .81$

SEE(%) = +55, -36

F = 21

where FT = flight-test cost (thousands of 1973 $)

Wt = airframe unit weight (lb)

Speed = maximum speed (kn)

N = number of test aircraft

DV = dummy variable (2 for cargo aircraft; 1 for all others).

VIII. QUALITY CONTROL

Quality control refers to the hours expended to ensure that prescribed standards are met. It includes such tasks as receiving inspection; in-process and final inspection of tools, parts, subassemblies, and complete assemblies; and reliability testing and failure-report reviewing. The preparation of reports relating to these tasks is considered direct quality-control effort.

Quality control is closely related to direct manufacturing labor but has been recorded as a separate account on most aircraft since about 1956 or 1957. Prior to that time it was treated as an overhead or burden charge. Our sample includes quality-control hours for 16 aircraft. It is difficult to generalize about those hours because they exhibit different patterns when looked at as a percentage of manufacturing labor hours. In some cases they are very high during the first lot or two, then they decline with each successive lot. In other cases they begin low and increase with cumulative quantity. If we look at the percentages at quantity 100, we find the following:

Aircraft Type	Ratio of Cumulative Quality-Control Hours to Cumulative Recurring Manufacturing Hours	Aircraft Type	Ratio of Cumulative Quality-Control Hours to Cumulative Recurring Manufacturing Hours
Attack	.103	Fighter	.114
Attack	.110	Fighter	.110
Bomber	.095	Fighter	.073
Bomber	.140	Fighter	.100
Cargo	.100	Fighter	.200
Cargo	.060	Fighter	.153
Cargo	.096	Trainer	.172
Fighter	.090	Trainer	.110

Cumulative quality-control hours per cumulative recurring manufacturing hours range from .06 to .10 for cargo aircraft, from .095 to .14 for bombers, from .073 to .20 for fighters, and from .11 to .172 for trainers. It appears that quality-control requirements on cargo

aircraft are below those of other types, but no distinction can be made among the others. Since quality-control hours are not correlated with the explanatory variables considered, we suggest that mean percentages be used: 8.5 percent of manufacturing labor hours for cargo aircraft, 12 percent for other types.

IX. TOTAL COST

As mentioned in the Introduction, a number of knowledgeable cost analysts believe that greater accuracy can be achieved by estimating airframe program cost in a lump sum rather than as the sum of several subordinate cost categories. Estimating in that way eliminates all the problems of deciding which costs are nonrecurring and which are recurring, which are tooling, which are engineering, etc. Estimating relationships, however, cannot be derived from recorded program costs adjusted only for price-level changes. All programs have to be put on a common basis, and that means assuming common wage rates and overhead rates. It is necessary to begin with labor hours and convert them into dollars. That conversion can result in a serious misstatement of cost if the correct hourly rates are not used, and we know of no way to assure that the correct hours will be used.

Table 9, which shows composite dollar rates for five major airframe companies for the year 1973, illustrates the problem. The composite rates include direct labor, overhead, general and administrative expense (G&A), miscellaneous direct charges (overtime premium, travel, per diem, miscellaneous taxes, etc.), and, in the case of tooling, material costs as well. As can be seen, the difference between the lowest and highest rate can be as much as 30 percent.

The differences in rates result from a variety of causes. Wage rates differ from one part of the country to another. They differ among companies, and within the same company they differ from one program to another. Burden rates vary substantially among companies. Accounting practices differ, e.g., one company may define the category *Other Direct Charges* more broadly than others, and that will increase the composite rate. Also, composite rates within a plant change from year to year as worker population and plant load change. As the work force and plant load build up, the composite hourly rate decreases; then, toward the end of a production program the rate rises again.

Figure 4 shows adjusted (i.e., converted to 1973 dollars) composite rates for one aircraft program over an 8-year period (but not

Table 9

COMPOSITE HOURLY RATES IN 1973 DOLLARS

Company	Engineering	Tooling	Quality Control	Manufacturing
A	21.13	21.86	16.19	15.39
B	21.75	16.76	16.26	15.39
C	18.00	17.84	19.61	16.19
D	19.88	18.93	16.12	17.81
E	19.55	17.80	15.95	14.06
Mean	20.06	18.63	16.83	15.77

to the end of the program). It is clear that if a program estimate is to be time-phased over the duration of the development and production period, some recognition of rate changes over time would be advisable.

We used the mean rates of Table 9 to convert labor hours into 1973 dollars. Total cost for 25, 50, 100, and 200 aircraft was then regressed against our list of independent variables. The best results,

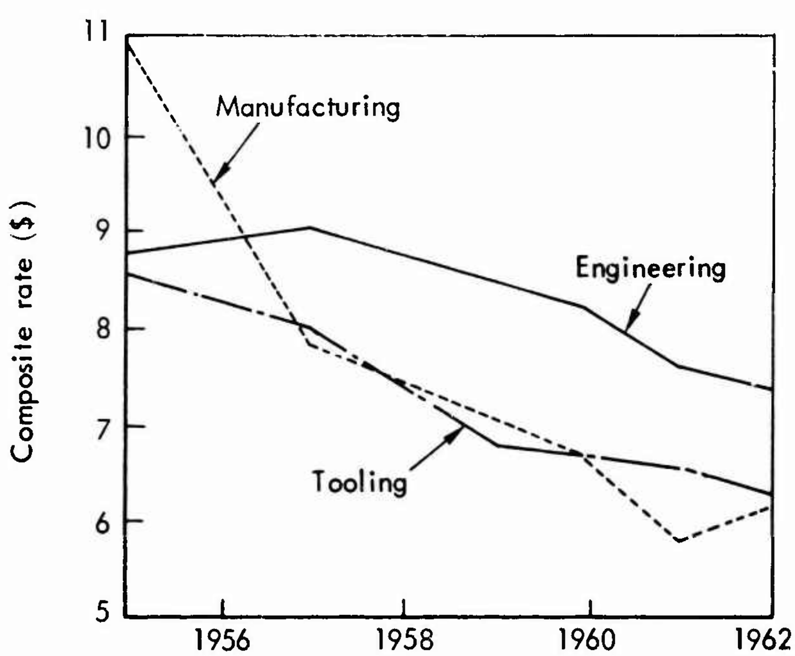

Fig.4 — Changes in hourly rate over time

shown below, appear quite good--better than those for the individual cost elements:

$$TC_{100} = 4.29(Wt)^{.73}_{1.00}(Speed)^{.74}_{.99}$$

$$R^2 = .88$$

$$SEE(\%) = +31, -24$$

$$F = 79$$

where TC_{100} = total cost for 100 units (thousands of 1973 $)
Wt = airframe unit weight (lb)
Speed = maximum speed (kn).

Up to this point, however, we have not added the individual cost elements together to obtain a total. When that is done using the same hourly rates to convert hours into cost, the results are comparable to those obtained for total cost, perhaps a little better. Table 10 presents the comparison. The range of Y-deviations obtained with the set of 7 equations is smaller and the mean is also smaller, but the correspondence is so close in most cases that neither method can be said to be preferred.

The total-cost equation has a serious deficiency, however. The equation is based on the composite rates above and cannot be adjusted to any other set of rates. One could assume (erroneously) that material costs, engineering labor, tooling labor, etc., increase at the same annual rate and in that manner adjust for inflation. But the basic problem is that the composite rates of Table 9 may not approximate those expected to be in effect for any specific program. In such a situation the total-cost equations would be of little value.

Table 10

COMPARISON OF Y-DEVIATIONS AT QUANTITY 100

(Percent)

Aircraft	Total Cost	Detailed Costs	Aircraft	Total Cost	Detailed Costs
A-3	-6	-9	F-3	-1	-6
A-4	18	18	F4D	26	23
A-5	-23	-18	F-4	0	0
A-6	-4	-8	F-14	-12	-6
B-52	4	-3	F-100	-81	-80
B-58	33	30	F-102	37	30
B/RB-66	-8	2	F-104	-49	-45
C-5	9	14	F-105	-21	-20
C-130	6	4	F-106	-10	-15
C-133	-6	-12	F-111	16	19
KC-135	-48	-44	T-38	-2	4
C-141	-43	-32	T-39	-42	-31
Absolute mean				21.0	19.7
Range				-81, +37	-80, +30

X. OTHER AVENUES EXPLORED

JUDGMENT

Table 10 shows that neither the total-cost equation nor the cost-element equations produce estimates that are consistently within 20 percent of the actual cost. Since the independent variables do not capture all elements of an aircraft program that contribute to cost, we considered using a judgmental factor.

A report by J. W. Noah et al. suggests that a complexity factor be entered in the estimating equations as a dummy variable, and that approach may have merit if estimators can agree on some measure of complexity.[1] We asked two Rand aeronautical engineers to evaluate program difficulty for aircraft with which they were familiar, using the simple definitions in Table 11. They agreed on 8 programs out of the 14 for which both felt qualified to express an opinion. They were one category apart on 5 aircraft and 2 categories apart on 1 aircraft (the B-52).

The agreement is good enough to suggest that a more carefully conducted survey might provide a fairly accurate technology index. The next question, however, is whether the index can be related to cost. From Table 11 one would expect the B-58, C-5, F-102, and F-111 to be underestimated by the model, and they are. One would not expect the model to vastly overestimate the F-100 and F-104, since they are both rated as being of medium difficulty.

We converted the estimates in Table 11 to numerical values by assigning a 1 for Minimum Problems, 3 for Some Problems, and 5 for Considerable Problems, and used these numbers as a third independent variable in a regression analysis. The results were actually poorer than those obtained without a difficulty index. A more carefully constructed experiment might produce different results, but we cannot recommend the equation developed here:

---

[1] J. Watson Noah Associates, Inc., *Estimating Aircraft Acquisition Costs by Parametric Methods*, FR-103-USN (Abridged), September 1973.

$$TC_{100} = 7.69\underset{.99}{(Wt)^{.69}}\underset{.89}{(Speed)^{.63}}\underset{.83}{(DI)^{.37}}$$

$$R^2 = .94$$

$$SEE(\%) = +37, -27$$

$$F = 25$$

where TC_{100} = total cost for 100 units (thousands of 1973 $)

Wt = airframe unit weight (lb)

Speed = maximum speed (kn)

DI = difficulty index.

Table 11

ESTIMATES OF PROGRAM DIFFICULTY

Aircraft	Minimum Problems	Some Problems	Considerable Problems
A-7	✓	✓	
B-52	✓		✓
B-58			✓✓
KC-135	✓	✓	
C-141	✓	✓	
C-5			✓✓
F-14		✓	✓
F-15		✓	✓
F-100		✓✓	
F-102			✓✓
F-104		✓✓	
F-105		✓	✓
F-106		✓✓	
F-111			✓✓
T-38	✓✓		

GROUPINGS

It is clearly more reasonable to work with a homogeneous sample than with one containing diverse and perhaps irrelevant data points. For that reason it is often argued that bombers and/or cargo aircraft should be treated as one sample, fighters as a separate sample, etc. We agree with the argument in principle but have three reservations about stratifying a sample of 25 aircraft. First, fighters, bombers, trainers, etc., are not meaningful categories: Some fighters are larger and faster than some bombers; a trainer may be larger and faster than some fighters. Thus whatever system of stratification is adopted, it must be based on a set of characteristics that clearly define the members of each subgroup in terms that have some rational relationship to cost.

Second, the subgroups tend to be too small to give results that are statistically valid if more than one independent variable is used. Estimating relationships based on small samples cannot be used outside the boundaries of the sample with any confidence.

Third, future aircraft may not fall in any of the subgroups. The B-1 strategic bomber, for example, would be outside any subgroup of previous aircraft. It is too fast to be categorized with the large aircraft (B-52, C-5, etc.) and too large to be placed with existing Mach 2 aircraft. It seems to us that only a sample containing both large aircraft and Mach 2 aircraft would provide a useful basis for estimating B-1 costs.

However, a number of possible ways of stratifying the samples were examined. The three groups that seemed to make the most sense are shown below:

Group 1	Group 2	Group 3
A-3	A-5	B-52
A-4	B-58	C-5
A-6	F-4	C-130
RB-66	F-14	C-133
F-3	F-104	KC-135
F4D	F-105	C-141
F-100	F-106	
F-102	F-111	
T-38		

Group 1 contains aircraft up to 30,000 lb, with speeds from 550 to 750 kn. Group 2 consists of 1,150-kn and faster aircraft with weights up to 35,000 lb. Group 3 has the larger and slower aircraft: weights of 43,000 to 280,000 lb, and speeds of 300 to 550 kn. Regression equations were derived for each cost element for each of the three groups. In most cases the results were not usable--the values of R^2 were low, explanatory variables had the wrong sign, the values of the coefficients were unreasonable, etc. Only in a very few cases were the estimates produced by the equations closer to the actual costs than those obtained using the full sample of 24 aircraft.

Much better results were obtained when we looked at total cost rather than the individual cost elements:

Group 1

$$TC_{100} = 2107(Wt)_{.99}^{.58}$$

$$R^2 = .63$$
$$SEE(\%) = +34, -25$$
$$F = 12$$

Group 2

$$TC_{100} = 10.43(Wt)_{.99}^{1.16}$$

$$R^2 = .93$$
$$SEE(\%) = +17, -15$$
$$F = 83$$

Group 3

$$TC_{100} = 24.16(Wt)_{.99}^{.96}$$

$$R^2 = .90$$
$$SEE(\%) = +24, -19$$
$$F = 38$$

where TC_{100} = total cost for 100 units (thousands of 1973 $)
Wt = airframe unit weight (lb).

As shown in Table 12, stratification reduces the Y-deviations in 15 of the 23 aircraft and increases them in 8. The biggest improvement occurs in Group 2, where Y-deviations are reduced to less than 20 percent for all aircraft but the A-5. Thus, when estimating in terms of total cost, a small, homogeneous sample may be preferred.

Table 12

COMPARISON OF Y-DEVIATIONS

Aircraft	Y-deviation (%) Subgroup	Y-deviation (%) Total Sample
Group 1		
A-3	-9	-6
A-4	-3	18
A-6	-2	-4
RB-66	8	8
F-3	-4	-1
F4D	19	26
F-100	-71	-81
F-102	38	37
T-38	-5	-2
Absolute mean	18	20
Group 2		
A-5	-30	-23
B-58	19	33
F-4	12	0
F-14	-9	-12
F-104	2	-49
F-105	-13	-21
F-106	6	-10
F-111	5	16
Absolute mean	12	21
Group 3		
B-52	25	4
C-5	5	9
C-130	12	6
C-133	-24	-6
KC-135	-8	-48
C-141	-19	-43
Absolute mean	16	19

XI. PROTOTYPE AIRCRAFT

Within the past few years increasing use of a fly-before-buy acquisition policy has led to several competitive prototype programs, including the YA-9 versus YA-10, YF-16 versus YF-17, and YC-14 versus YC-15. Such programs emphasize early demonstration of technical feasibility before a commitment is made to produce for inventory. Because they have little or no production planning, limited tooling, fewer test articles, and, sometimes, limited systems development, they are not directly comparable to full-scale development programs. Hence the cost of a prototype program of 2 or 3 aircraft cannot be estimated with either the detailed model or the total-cost model described previously.

Unfortunately, there is little homogeneity among prototype programs. People tend to think of the F-104 and Lockheed's famous Skunk Works when prototypes are mentioned, but the F-104 is far from a typical prototype program. It belongs at that end of the spectrum where no provisions for production are included in the program. At the other end we find aircraft such as the T-38 which incurred over 3 times as many engineering hours as did the F-104 and over 10 times as many tooling hours.

The problem is one of definition and of sample size. If we define a prototype program as one in which the first lot consists of 3 aircraft or less, we clearly will include programs in which preproduction costs are incurred in the first lot. If we define a prototype program as one in which no thought whatsoever is given to production considerations, our sample will dwindle to a very few aircraft, most of which date back to the late 1940s and early 1950s. However, we initially used all 16 aircraft listed below to derive prototype estimating equations for each major cost element:

A-3	[F3D]	[F-86D]
A-4	F3H	[F-89]
[B-47]	F4D	F-100
B-52	[F-84]	F-104
C-130	[F-86A]	T-38
KC-135		

The results were poor statistically. Moreover, when the estimates they gave for contemporary programs were compared with known costs, it appeared that the equations were not reliable.

The 6 oldest aircraft--those in brackets--were then deleted from the sample, and a second attempt was made to derive estimating equations for each major cost element. Again, as shown in Table 13, the results were discouraging. Because of complementarities among cost elements it appeared that combining those elements and dealing with

Table 13

RESULTS OF MULTIPLE-REGRESSION ANALYSIS FOR PROTOTYPE AIRFRAMES

		Independent Variable					
		Weight		Speed		Quantity	
Cost Element	R^2	T-ratio	LS[a]	T-ratio	LS[a]	T-ratio	LS[a]
Engineering hours	.166	1.027	.66	.118	.09	---	---
Tooling hours	.404	1.561	.84	-.334	.25	---	---
Manufacturing hours	.590	3.175	.98	---	---	.62	.45
Manufacturing material	.356	.793	.55	---	---	1.914	.90
Flight-test cost	.189	.829	.57	1.274	.76	---	---

[a]Level of significance.

total prototype program cost might give better results. When that was done, the equation below was obtained:

$$TC_p = 1115.4(Wt)^{.35}(N)^{.99}$$

$$R^2 = .75$$

$$SEE(\%) = +36, -26$$

$$F = 10.4$$

where TC_p = total prototype program cost (thousands of 1973 \$)

Wt = airframe unit weight (lb)

N = prototype aircraft.

Speed was not significant in the regression analysis, probably because the only Mach 2 aircraft in the sample, the F-104, had almost the lowest cost. The equation approximates the cost of current prototype programs fairly well, but this is clearly an area in which further research is required.

Another possible method for estimating the cost of prototype programs would be to assume that the engineering hours, tooling hours, etc., expended for the first few aircraft would be some constant percentage of the hours required for the same number of aircraft in a full-scale development program. For example, it would be convenient if the engineering hours required for two prototype aircraft turned out to be, say, 50 percent of the hours that would be estimated for two aircraft using equations previously derived. Unfortunately, as shown in Fig. 5, the value ranges from 37 percent to 79 percent. The range for manufacturing labor hours is comparable, and that for manufacturing materials is even wider--from 50 to 127 percent. Tooling is the only cost element for which agreement is good enough that one might consider using a mean value for estimating purposes.

When an estimate of both a prototype program and subsequent development prior to production is required, we assume that total development cost does not change because of the prototype program: prototype development plus subsequent development equals total development.

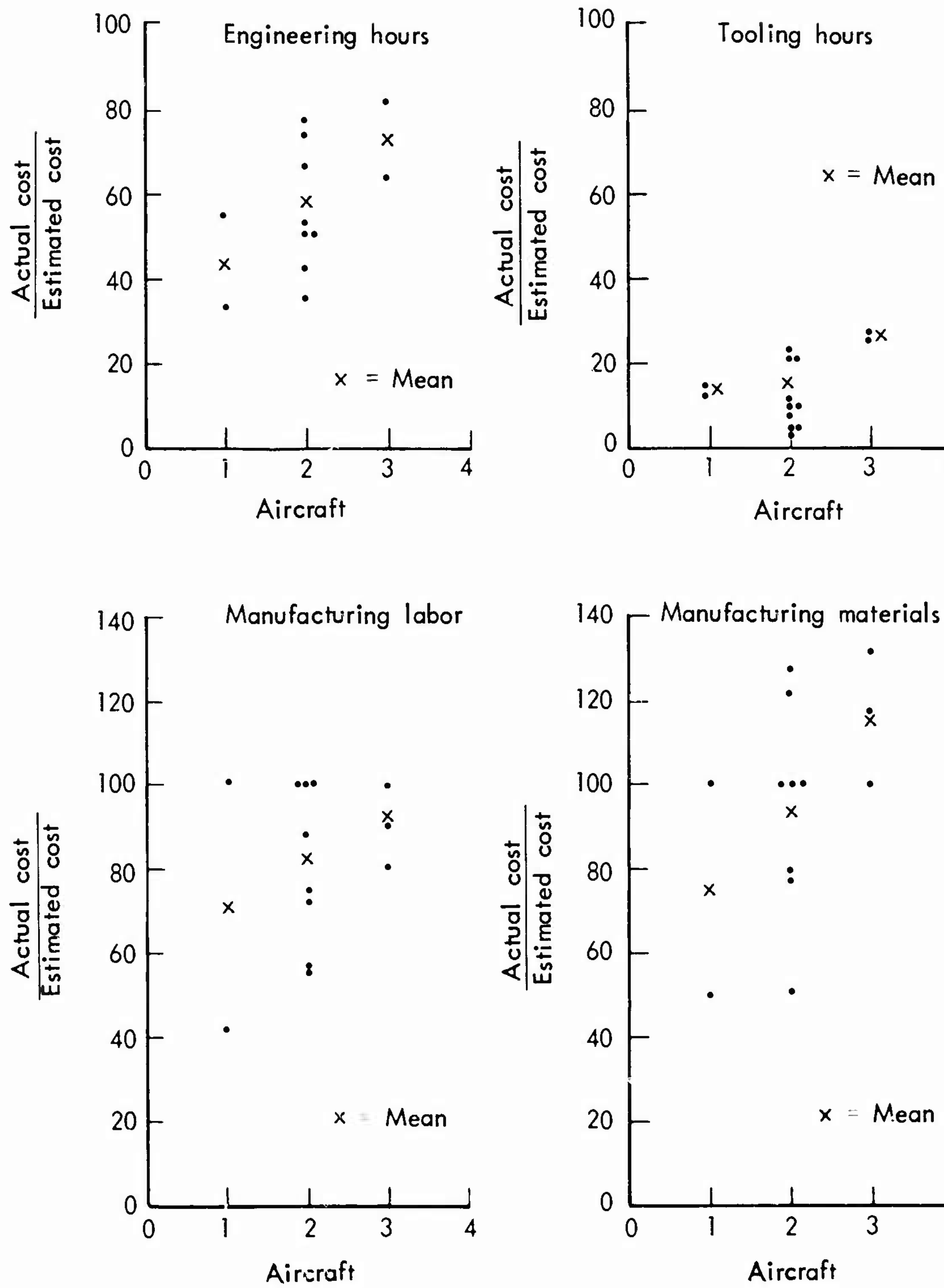

Fig. 5—Actual cost/estimated cost versus number of prototype aircraft

XII. CONCLUSIONS

No study of the type described here is ever complete. One analysis leads to another ad infinitum, until at some point it is necessary to call a halt, present the results, and go on to something else. We have gone down a number of paths suggested by persons inside and outside of Rand and found that most terminate in a cul-de-sac. None of the many independent variables considered offers much hope of improving the reliability of estimates obtained using only weight and speed. Estimating in terms of total cost rather than individual cost elements is no more accurate, is less useful because of the lack of detail, and is more difficult because of the need to assume hourly rates and translate hours into dollars. Incorporating a subjective index of difficulty improves some estimates but degrades others even if agreement can be reached on the degree of difficulty a new program poses. Stratification of the sample of airframes can greatly reduce the Y-deviations but at some cost--one independent variable may become statistically insignificant, and extrapolation outside the boundaries of the sample becomes very risky.

The present study has resulted in a set of estimating equations similar to those developed in previous Rand studies in that the primary explanatory variables are weight and speed. We believe that the equations are useful and that they approximate the cost of new airframe development and production programs well enough to be used for planning purposes.

But it may be time for a change in direction. As stated in the Introduction, use of a parametric model implies a belief that all programs will have neither more nor less than their fair share of problems, yet we know that some programs are plagued with problems that are not a function of aircraft characteristics. It might be productive to examine the influence of what might be called program characteristics on program cost. For example, all contractors talk about the importance of schedule--the cost of trying to produce an aircraft too quickly and the cost of schedule changes. Also, however, it is widely believed that producing aircraft too slowly, once development has been completed,

increases cost. An investigation of the effect of schedule on cost might be more fruitful than looking at aircraft characteristics in more detail.

Contractor experience is another factor sometimes cited as an explanation for cost differences. For example, all things being equal, one would expect McDonnell Aircraft Company, because of its current experience on the F-4, to produce the F-15 more cheaply than a company that had not built a fighter aircraft for 10 years. Perhaps a currency-of-experience factor would be a useful variable.

We should also take a look at complementarities. It is generally believed, for example, that an increase in tooling hours should be offset by a decrease in factory labor hours. Can we detect such tradeoffs using the data available, and if so, should they be incorporated in the model? Does a greater expenditure of engineering hours during the development phase reduce expenditures for modifications and retrofits later in a program?

Another interesting relationship is the one between manufacturing hours at unit one and manufacturing hours at some larger quantity, say, 100 or 200. We know that learning-curve slope is highly correlated with unit-one cost--an airframe that requires an abnormally high number of hours for the first few units will have a steeper than average slope. It would be useful to be able to predict which programs are likely to have that experience.

The point we wish to make, however, is broader than these specific suggestions. It is that the premise on which this and previous studies have been based is deterministic, viz., if an airplane has a certain weight and speed, it will have a certain cost. Schedule, experience, efficiency, economic conditions, labor scarcities, and all the other problems contractors worry about are assumed to have no influence on cost. It may be true that such influences are neither important enough nor consistent enough to be detected by regression analyses of aggregated data, but that in itself would be worth knowing. We believe that future research should place less emphasis on trying to explain cost differences on the basis of physical and performance characteristics and more emphasis on trying to understand the influence of program differences.

Appendix A

AN ILLUSTRATIVE PROBLEM

To illustrate the use of the estimating equations presented in this study, we shall consider a hypothetical aircraft program for a fighter with an airframe unit weight of 25,000 lb and a maximum speed of 1,250 kn. The development program includes production of 20 flight-test aircraft. Following development, 250 aircraft will be produced for operational purposes. First flight of a production aircraft is scheduled for June 1978.

In this example we shall show only one equation for each cost element, but the results of alternative equations are shown in the summary tables on p. 61. Table numbers given at the right of each equation indicate the source of that equation. All calculations have been rounded to the nearest thousand.

We have chosen numbers of aircraft other than the 25, 50, 100, and 200 for which equations are given to show how the equations can be used for interpolation and extrapolation. The procedure adopted here for 20 airframes is to calculate values at 25 and 50 and obtain a unit-one value and cost-quantity curve slope as follows:

By definition, Y_{50}/Y_{25} = slope (S), in percentage terms. The exponent b in the cost-quantity curve equation $Y = aX^b$ is

$$b = \frac{\text{Log } S}{\text{Log } 2}$$

$$Y_{25} = Y_1(25)^b$$

$$Y_1 = \frac{Y_{25}}{(25)^b}$$

$$Y_{20} = Y_1(20)^b \ .$$

Similarly, for 250 production aircraft we calculate values at 100 and 200 to obtain a slope for extrapolation out to 270 (20 development airframes plus 250 production). Note that Y_1 is a construct, not a real value. Its value will change as different cost-quantity curve slopes are derived.

Engineering

1. 20 development airframes:

$$E_{25} = .0609W^{.631}S^{.820} \qquad \text{(Table 9)}$$

$$= .0609(25{,}000)^{.631}(1250)^{.820}$$

$$= 12{,}566 \text{ (in thousands)}$$

$$= 12{,}566{,}000 \text{ hr}$$

$$E_{20} = E_1(20)^{.221}$$

$$= 6{,}170{,}000(1938)$$

$$= 11{,}961{,}000 \text{ hr}$$

Engineering cost = 11,961,000 hr ($20.06/hr)

= $239,938,000

2. 250 production airframes:

$$E_{200} = .02W^{.664}S^{.987} \qquad \text{(Table 12)}$$

$$= .02(25{,}000)^{.664}(1250)^{.987}$$

$$= 18{,}886 \text{ (in thousands)}$$

$$= 18{,}886{,}000$$

$$E_{270} = E_1(270)^{.112}$$

$$= 10{,}408{,}000(1.87)$$

$$= 19{,}484{,}000$$

$$E_{270} - E_{20} = 7{,}523{,}000 \text{ hr}$$

Engineering cost = 7,523,000 hr ($20.06/hr)

= $150,911,000

Tooling

1. 20 development airframes:

$$T_{25} = .118W^{.727}S^{.508} \qquad \text{(Table 13)}$$

$$= 6957 \text{ (in thousands)}$$

$$= 6{,}957{,}000 \text{ hr}$$

$$T_{20} = T_1(20)^{.216}$$

$$= 3{,}471{,}000(1.91)$$

$$= 6{,}629{,}000 \text{ hr}$$

$$\text{Tooling cost} = 6{,}629{,}000 \text{ hr } (\$18.63/\text{hr})$$

$$= \$123{,}498{,}000$$

2. 250 production airframes:

$$T_{200} = .522W^{.621}S^{.532} \qquad \text{(Table 16)}$$

$$= 12{,}483 \text{ (in thousands)}$$

$$= 12{,}483{,}000$$

$$T_{270} = T_1(270)^{.236}$$

$$= 3{,}575{,}000(3.748)$$

$$= 13{,}399{,}000$$

$$T_{270} - T_{20} = 6{,}770{,}000$$

$$\text{Tooling cost} = 6{,}770{,}000 \text{ hr } (\$18.63/\text{hr})$$

$$= \$126{,}125{,}000$$

Nonrecurring Manufacturing Labor

Development Airframes

$$H_{NR} = .000626W^{.688}S^{1.211} \qquad \text{(Table 17)}$$

$$= .000626(25{,}000)^{.688}(1250)^{1.211}$$

$$= 3739 \text{ (in thousands)}$$

$$= 3{,}739{,}000 \text{ hr}$$

Nonrecurring manufacturing labor cost = 3,739,000 hr (\$15.77/hr)

= \$58,964,000

Recurring Manufacturing Labor

1. 20 development airframes:

$$H_{25} = .796W^{.735}S^{.258} \qquad \text{(Table 22)}$$

$$= .796(25{,}000)^{.735}(1250)^{.258}$$

$$= 8559 \text{ (in thousands)}$$

$$= 8{,}559{,}000 \text{ hr}$$

$$H_{20} = H_1(20)^{.675}$$

$$= 975{,}000(7.554)$$

$$= 7{,}365{,}000 \text{ hr}$$

Recurring manufacturing labor cost = 7,365,000 hr (\$15.77/hr)

= \$116,146,000

2. 250 production airframes:

$$G_{200} = .582W^{.783}S^{.430} \qquad \text{(Table 25)}$$

$$= .582(25{,}000)^{.783}(1250)^{.430}$$

$$= 34{,}688 \text{ (in thousands)}$$

$$= 34{,}688{,}000 \text{ hr}$$

$$H_{270} = H_1(270)^{.647}$$

$$= 1{,}126{,}000(37.419)$$

$$= 42{,}134{,}000$$

$$H_{270} - H_{20} = 34{,}769{,}000 \text{ hr}$$

Recurring manufacturing labor cost = 34,769,000 hr (\$15.77/hr)

= \$548,307,000

Nonrecurring Materials Cost

20 development airframes:

$$M_{NR} = .000024W^{.724}S^{1.924} \quad \text{(Table 26)}$$

$$= .000024(25{,}000)^{.724}(1250)^{1.924}$$

$$= 33{,}325 \text{ (in thousands)}$$

$$= \$33{,}325{,}000$$

Recurring Materials

1. 20 development airframes:

$$M_{25} = .00478W^{.918}S^{1.004} \quad \text{(Table 27)}$$

$$= .00478(25{,}000)^{.918}(1250)^{1.004}$$

$$= 66{,}994 \text{ (in thousands)}$$

$$= \$66{,}994{,}000$$

$$M_{20} = M_1(20)^{.699}$$

$$= 7{,}061{,}000(8.117)$$

$$\text{Cost} = \$57{,}317{,}000$$

2. 250 production airframes:

$$M_{200} = .151W^{.860}S^{.813} \quad \text{(Table 30)}$$

$$= .151(25{,}000)^{.860}(1250)^{.813}$$

$$= 301{,}296 \text{ (in thousands)}$$

$$= \$301{,}296{,}000$$

$$M_{270} = M_1(270)^{.751}$$

$$= 5{,}635{,}000(66.981)$$

$$= 377{,}440{,}000$$

$$M_{270} - M_{20} = \$320{,}123{,}000$$

Flight Test

20 development airframes:

$$FT = .130W^{.710}S^{.586}N^{.716}DV^{-1.557} \qquad \text{(Table 35)}$$

$$= .13(25,000)^{.71}(1250)^{.586}(20)^{.716}(1)^{-1.557}$$

$$= 96,119 \text{ (in thousands)}$$

$$= \$96,119,000$$

Quality Control

20 development airframes:

$$\text{QC hours} = .12 \text{ (nonrecurring + recurring labor hours)}$$

$$= .12(3,739,000 + 7,365,000)$$

$$= 1,332,000 \text{ hr}$$

$$\text{QC cost} = (\$16.83/\text{hr})(1,332,000)$$

$$= \$22,418,000$$

250 production airframes:

$$\text{QC hours} = (.131)(34,769,000)$$

$$= 4,172,000$$

$$\text{QC cost} = (\$16.83/\text{hr})(4,207,000)$$

$$= \$70,215,000$$

Development Cost (in millions of 1973 $)

Cost Element	Cost from Example	Alternative Estimates	
		Full Sample	With Time
Engineering	239.938	204.311	346.236
Tooling	123.498	---	---
Nonrecurring manufacturing labor	58.964	---	---
Recurring manufacturing labor	116.146	---	84.874
Nonrecurring manufacturing materials	33.325	---	---
Recurring manufacturing materials	57.317	---	77.419
Flight test	96.119	---	---
Quality control	22.418	---	17.2[illegible]0
Total	744.875	709.443	837.695

Production Cost

Cost Element	Cost from Example	Alternative Estimates	
		Full Sample	With Time
Engineering	150.911	126.719	138.153
Tooling	126.125	---	---
Recurring manufacturing labor	543.307	---	406.897
Recurring manufacturing materials	320.123	---	440.571
Quality control	70.215	---	52.110
Total	1215.681	1192.079	1163.856
Total program	1960.555	1901.522	2001.551
Estimate using total-cost equation	1947.278	---	---
Estimate using Group 2 equation	1994.539	---	---

Appendix B

REGRESSION EQUATIONS AND STATISTICS

Table B-1

ENGINEERING HOURS FOR 25 AIRFRAMES VS WEIGHT, SPEED, TIME

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2 + D * LN X3

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-7.40975
A	0.60532D-03
B	0.66231
C	0.93231
D	0.77145
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.92012
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.84662
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.36220
COEFFICIENT OF VARIATION (PERCENT)	4.22815
SUM OF SQUARES OF Y RESIDUALS	2.62376
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	28.90798
DURBIN-WATSON STATISTIC	2.08770
F VALUE	36.79863
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	20.
DEGREES OF FREEDOM DUE TO REGRESSION	3.
TOTAL DEGREES OF FREEDOM	23.
NUMBER OF DATA POINTS	24.

VARIABLES	MEANS	STD DEV
Y	8.56636	0.86241
X1	10.07749	1.03004
X2	6.55430	0.43717
X3	4.13651	0.26604

CORRELATION MATRIX

	Y	X1	X2	X3
Y	1.00000	0.70971	0.28478	0.63293
X1	0.70971	1.00000	-0.33046	0.31452
X2	0.28478	-0.33046	1.00000	0.30926
X3	0.63293	0.31452	0.30926	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.67576	-4.42174	-0.99974	
B	0.08771	7.55089	1.00000	0.79104
C	0.20629	4.51942	0.99979	0.47260
D	0.33705	2.28884	0.96690	0.23798

Table B-2

ENGINEERING HOURS FOR 50 AIRFRAMES VS WEIGHT, SPEED, TIME

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2 + D * LN X3

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-7.18766
A	0.755860-03
B	0.67313
C	0.94997
D	0.69765
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.92268
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.85135
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.35453
COEFFICIENT OF VARIATION (PERCENT)	4.07137
SUM OF SQUARES OF Y RESIDUALS	2.51389
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	27.87806
DURBIN-WATSON STATISTIC	2.23254
F VALUE	38.18009
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	20.
DEGREES OF FREEDOM DUE TO REGRESSION	3.
TOTAL DEGREES OF FREEDOM	23.
NUMBER OF DATA POINTS	24.

VARIABLES	MEANS	STD DEV
Y	8.70800	0.85747
X1	10.07749	1.03004
X2	6.55430	0.43717
X3	4.13651	0.26604

CORRELATION MATRIX

	Y	X1	X2	X3
Y	1.00000	0.71662	0.28405	0.62055
X1	0.71662	1.00000	-0.33046	0.31452
X2	0.28405	-0.33046	1.00000	0.30926
X3	0.62055	0.31452	0.30926	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.64030	-4.38193	-0.99971	
B	0.08586	7.84014	1.00000	0.80859
C	0.20192	4.70460	0.99986	0.48433
D	0.32992	2.11463	0.95279	0.21645

Table B-3

ENGINEERING HOURS FOR 100 AIRFRAMES VS WEIGHT, SPEED, TIME

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2 + D * LN X3

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-7.11782
A	0.81053D-03
B	0.67225
C	0.99154
D	0.64821
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.92751
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.86027
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.34034
COEFFICIENT OF VARIATION (PERCENT)	3.85129
SUM OF SQUARES OF Y RESIDUALS	2.31656
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	25.78494
DURBIN-WATSON STATISTIC	2.29745
F VALUE	41.04295
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	20.
DEGREES OF FREEDOM DUE TO REGRESSION	3.
TOTAL DEGREES OF FREEDOM	23.
NUMBER OF DATA POINTS	24.

VARIABLES	MEANS	STD DEV
Y	8.83692	0.84900
X1	10.07749	1.03004
X2	6.55430	0.43717
X3	4.13651	0.26604

CORRELATION MATRIX

	Y	X1	X2	X3
Y	1.00000	0.71076	0.30386	0.61754
X1	0.71076	1.00000	-0.33046	0.31452
X2	0.30386	-0.33046	1.00000	0.30926
X3	0.61754	0.31452	0.30926	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.57460	-4.52039	-0.99979	
B	0.08242	8.15658	1.00000	0.81560
C	0.19384	5.11535	0.99995	0.51057
D	0.31670	2.04673	0.94595	0.20312

Table B-4

ENGINEERING HOURS FOR 200 AIRFRAMES VS WEIGHT, SPEED, TIME

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2 + D * LN X3

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-6.74094
A	0.118150-02
B	0.67858
C	0.99022
D	0.57481
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.92713
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.85958
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.33784
COEFFICIENT OF VARIATION (PERCENT)	3.76825
SUM OF SQUARES OF Y RESIDUALS	2.28267
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	25.17930
DURBIN-WATSON STATISTIC	2.32394
F VALUE	40.80949
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	20.
DEGREES OF FREEDOM DUE TO REGRESSION	3.
TOTAL DEGREES OF FREEDOM	23.
NUMBER OF DATA POINTS	24.

VARIABLES	MEANS	STD DEV
Y	8.96535	0.84070
X1	10.07749	1.03004
X2	6.55430	0.43717
X3	4.13651	0.26604

CORRELATION MATRIX

	Y	X1	X2	X3
Y	1.00000	0.71845	0.29642	0.60264
X1	0.71845	1.00000	-0.33046	0.31452
X2	0.29642	-0.33046	1.00000	0.30926
X3	0.60264	0.31452	0.30926	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.56304	-4.31271	-0.99966	
B	0.08181	8.29430	1.00000	0.83141
C	0.19241	5.14630	0.99995	0.51492
D	0.31438	1.82842	0.91756	0.18190

Table B-5

ENGINEERING HOURS FOR 25 AIRFRAMES VS WEIGHT, SPEED

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-6.58523
A	0.138060D-02
B	0.75552
C	1.15006
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.89802
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.80644
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.39707
COEFFICIENT OF VARIATION (PERCENT)	4.63527
SUM OF SQUARES OF Y RESIDUALS	3.31102
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	31.56722
DURBIN-WATSON STATISTIC	1.17601
F VALUE	43.74814
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	23.
NUMBER OF DATA POINTS	24.

VARIABLES	MEANS	STD DEV
Y	8.56636	0.86241
X1	10.07749	1.03004
X2	6.55430	0.43717

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.70971	0.28478
X1	0.70971	1.00000	-0.33046
X2	0.28478	-0.33046	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.79416	-3.67037	-0.99858	
B	0.08517	8.87113	1.00000	0.90237
C	0.20066	5.73129	0.99999	0.58298

Table B-6

ENGINEERING HOURS FOR 50 AIRFRAMES VS WEIGHT, SPEED

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-6.44201
A	0.15932D-02
B	0.75742
C	1.14690
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.90449
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.81811
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.38272
COEFFICIENT OF VARIATION (PERCENT)	4.39503
SUM OF SQUARES OF Y RESIDUALS	3.07596
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	31.37971
DURBIN-WATSON STATISTIC	1.36661
F VALUE	47.22690
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	23.
NUMBER OF DATA POINTS	24.

VARIABLES	MEANS	STD DEV
Y	8.70800	0.85747
X1	10.07749	1.03004
X2	6.55430	0.43717

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.71662	0.28405
X1	0.71662	1.00000	-0.33046
X2	0.28405	-0.33046	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.72930	-3.72521	-0.99875	
B	0.08209	9.22704	1.00000	0.90985
C	0.19341	5.92987	0.99999	0.58473

Table B-7

ENGINEERING HOURS FOR 100 AIRFRAMES VS WEIGHT, SPEED

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-6.42502
A	0.162050-02
B	0.75057
C	1.17451
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.91159
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.83100
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.36526
COEFFICIENT OF VARIATION (PERCENT)	4.13339
SUM OF SQUARES OF Y RESIDUALS	2.80178
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	29.33928
DURBIN-WATSON STATISTIC	1.44563
F VALUE	51.62931
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	23.
NUMBER OF DATA POINTS	24.

VARIABLES	MEANS	STD DEV
Y	8.83692	0.84900
X1	10.07749	1.03004
X2	6.55430	0.43717

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.71076	0.30386
X1	0.71076	1.00000	-0.33046
X2	0.30386	-0.33046	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.65043	-3.89293	-0.99916	
B	0.07834	9.58050	1.00000	0.91062
C	0.18459	6.36285	1.00000	0.60478

Table B-8

ENGINEERING HOURS FOR 200 AIRFRAMES VS WEIGHT, SPEED

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-6.12658
A	0.21840D-02
B	0.74803
C	1.15247
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.91439
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.83611
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.35619
COEFFICIENT OF VARIATION (PERCENT)	3.97291
SUM OF SQUARES OF Y RESIDUALS	2.66423
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	28.29870
DURBIN-WATSON STATISTIC	1.57769
F VALUE	53.56594
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	23.
NUMBER OF DATA POINTS	24.

VARIABLES	MEANS	STD DEV
Y	8.96535	0.84070
X1	10.07749	1.03004
X2	6.55430	0.43717

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.71845	0.29642
X1	0.71845	1.00000	-0.33046
X2	0.29642	-0.33046	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.60941	-3.80673	-0.99897	
B	0.07640	9.79150	1.00000	0.91650
C	0.18000	6.40259	1.00000	0.59929

Table B-9

ENGINEERING HOURS FOR 25 AIRFRAMES--SMALL SAMPLE

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-2.79828
A	0.60915D-01
B	0.63141
C	0.82040
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.95244
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.90714
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.23610
COEFFICIENT OF VARIATION (PERCENT)	2.53956
SUM OF SQUARES OF Y RESIDUALS	0.33446
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	16.64284
DURBIN-WATSON STATISTIC	2.94966
F VALUE	29.30753
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	6.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	8.
NUMBER OF DATA POINTS	9.

VARIABLES	MEANS	STD DEV
Y	9.29691	0.67099
X1	10.36012	1.12772
X2	6.76955	0.42641

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.82995	0.05066
X1	0.82995	1.00000	-0.44355
X2	0.05066	-0.44355	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	2.01170	-1.39100	-0.78638	
B	0.08259	7.64521	0.99974	1.06119
C	0.21842	3.75601	0.99056	0.52135

Table B-10

ENGINEERING HOURS FOR 50 AIRFRAMES--SMALL SAMPLE

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-3.31413
A	0.36366D-01
B	0.64335
C	0.89705
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.95263
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.90751
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.24074
COEFFICIENT OF VARIATION (PERCENT)	2.55465
SUM OF SQUARES OF Y RESIDUALS	0.34774
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	17.67481
DURBIN-WATSON STATISTIC	2.83757
F VALUE	29.43605
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	6.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	8.
NUMBER OF DATA POINTS	9.

VARIABLES	MEANS	STD DEV
Y	9.42365	0.68554
X1	10.36012	1.12772
X2	6.76955	0.42641

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.81082	0.08855
X1	0.81082	1.00000	-0.44355
X2	0.08855	-0.44355	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	2.05124	-1.61567	-0.84271	
B	0.08421	7.63960	0.99974	1.05831
C	0.22272	4.02777	0.99310	0.55797

Table B-11

ENGINEERING HOURS FOR 100 AIRFRAMES--SMALL SAMPLE

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-3.75348
A	0.23436D-01
B	0.65598
C	0.95992
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.94627
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.89543
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.26357
COEFFICIENT OF VARIATION (PERCENT)	2.76259
SUM OF SQUARES OF Y RESIDUALS	0.41682
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	18.85491
DURBIN-WATSON STATISTIC	2.61251
F VALUE	25.69028
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	6.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	8.
NUMBER OF DATA POINTS	9.

VARIABLES	MEANS	STD DEV
Y	9.54080	0.70589
X1	10.36012	1.12772
X2	6.76955	0.42641

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.79079	0.11502
X1	0.79079	1.00000	-0.44355
X2	0.11502	-0.44355	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	2.24578	-1.67135	-0.85431	
B	0.09220	7.11487	0.99961	1.04799
C	0.24384	3.93670	0.99235	0.57986

Table B-12

ENGINEERING HOURS FOR 200 AIRFRAMES--SMALL SAMPLE

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-3.91041
A	0.20032D-01
B	0.66360
C	0.98708
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.94161
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.88663
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.27936
COEFFICIENT OF VARIATION (PERCENT)	2.89596
SUM OF SQUARES OF Y RESIDUALS	0.46826
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	19.37525
DURBIN-WATSON STATISTIC	2.44382
F VALUE	23.46196
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	6.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	8.
NUMBER OF DATA POINTS	9.

VARIABLES	MEANS	STD DEV
Y	9.64666	0.71854
X1	10.36012	1.12772
X2	6.76955	0.42641

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.78167	0.12382
X1	0.78167	1.00000	-0.44355
X2	0.12382	-0.44355	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	2.38033	-1.64280	-0.84847	
B	0.09772	6.79062	0.99950	1.04149
C	0.25845	3.81930	0.99123	0.58577

Table B-13

TOOLING HOURS FOR 25 AIRFRAMES

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-2.13739
A	0.11796
B	0.72713
C	0.50821
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.85777
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.73577
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.44000
COEFFICIENT OF VARIATION (PERCENT)	5.17830
SUM OF SQUARES OF Y RESIDUALS	4.25915
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	34.62077
DURBIN-WATSON STATISTIC	2.15045
F VALUE	30.62968
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	22.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	8.49695	0.81952
X1	10.04981	1.01849
X2	6.54767	0.42925

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.81973	-0.01876
X1	0.81973	1.00000	-0.31532
X2	-0.01876	-0.31532	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.95294	-1.09445	-0.71440	
B	0.09292	7.82496	1.00000	0.90366
C	0.22048	2.30495	0.96902	0.26619

Table B-14

TOOLING HOURS FOR 50 AIRFRAMES

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-1.17748
A	0.30806
B	0.67377
C	0.47912
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.84855
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.72004
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.42418
COEFFICIENT OF VARIATION (PERCENT)	4.85872
SUM OF SQUARES OF Y RESIDUALS	3.95838
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	33.49742
DURBIN-WATSON STATISTIC	2.17645
F VALUE	28.29192
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	22.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	8.73023	0.76755
X1	10.04881	1.01849
X2	6.54767	0.42925

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.80956	-0.01397
X1	0.80956	1.00000	-0.31532
X2	-0.01397	-0.31532	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.88273	-0.62541	-0.46186	
B	0.08958	7.52120	1.00000	0.89405
C	0.21256	2.25407	0.96551	0.26794

Table B-15

TOOLING HOURS FOR 100 AIRFRAMES

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-0.75015
A	0.47229
B	0.63801
C	0.49908
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.84172
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.70849
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.41319
COEFFICIENT OF VARIATION (PERCENT)	4.62751
SUM OF SQUARES OF Y RESIDUALS	3.75589
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	32.75785
DURBIN-WATSON STATISTIC	2.28926
F VALUE	26.73501
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	22.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	8.92889	0.73270
X1	10.04881	1.01849
X2	6.54767	0.42925

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.79467	0.01273
X1	0.79467	1.00000	-0.31532
X2	0.01273	-0.31532	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.83394	-0.40904	-0.31354	
B	0.08726	7.31148	1.00000	0.88687
C	0.20705	2.41043	0.97527	0.29238

Table B-16

TOOLING HOURS FOR 200 AIRFRAMES

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-0.64933
A	0.52239
B	0.62136
C	0.53225
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.83620
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.69924
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.41187
COEFFICIENT OF VARIATION (PERCENT)	4.53619
SUM OF SQUARES OF Y RESIDUALS	3.73199
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	33.20448
DURBIN-WATSON STATISTIC	2.16504
F VALUE	25.57366
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	22.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	9.07961	0.71904
X1	10.04881	1.01849
X2	6.54767	0.42925

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.77995	0.04021
X1	0.77995	1.00000	-0.31532
X2	0.04021	-0.31532	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.82809	-0.35520	-0.27417	
B	0.08698	7.14346	1.00000	0.88014
C	0.20639	2.57885	0.93287	0.31774

Table B-17

NONRECURRING MANUFACTURING LABOR HOURS

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-7.37620
A	0.62597D-03
B	0.68833
C	1.21089
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.72627
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.52747
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.72442
COEFFICIENT OF VARIATION (PERCENT)	9.66285
SUM OF SQUARES OF Y RESIDUALS	11.02044
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	60.30124
DURBIN-WATSON STATISTIC	2.62561
F VALUE	11.72065
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	23.
NUMBER OF DATA POINTS	24.

VARIABLES	MEANS	STD DEV
Y	7.49695	1.00698
X1	10.07749	1.03004
X2	6.55430	0.43717

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.53037	0.29302
X1	0.53037	1.00000	-0.33046
X2	0.29302	-0.33046	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	3.27325	-2.25348	-0.96496	
B	0.15538	4.43007	0.99977	0.70409
C	0.36609	3.30763	0.99665	0.52570

Table B-18

RECURRING MANUFACTURING LABOR HOURS FOR 25 AIRFRAMES VS WEIGHT, SPEED, TIME

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2 + D * LN X3

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	0.73180
A	2.07882
B	0.79874
C	0.41443
D	-0.63285
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.91459
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.83647
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.34866
COEFFICIENT OF VARIATION (PERCENT)	3.94266
SUM OF SQUARES OF Y RESIDUALS	2.55288
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	28.27553
DURBIN-WATSON STATISTIC	2.67711
F VALUE	35.80594
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	3.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	8.84334	0.80652
X1	10.04881	1.01849
X2	6.54767	0.42925
X3	4.15321	0.27349

CORRELATION MATRIX

	Y	X1	X2	X3
Y	1.00000	0.88470	-0.15544	0.10073
X1	0.88470	1.00000	-0.31532	0.25356
X2	-0.15544	-0.31532	1.00000	0.27005
X3	0.10073	0.25356	0.27005	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.60929	0.45474	0.34604	
B	0.07928	10.07444	1.00000	1.00867
C	0.18899	2.19284	0.96028	0.22057
D	0.29101	-2.17468	-0.95877	-0.21460

Table B-19

RECURRING MANUFACTURING LABOR HOURS FOR 50 AIRFRAMES VS WEIGHT, SPEED, TIME

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2 + D * LN X3

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	0.36577
A	1.44163
B	0.81655
C	0.48453
D	-0.59477
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.92877
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.86261
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.32080
COEFFICIENT OF VARIATION (PERCENT)	3.45936
SUM OF SQUARES OF Y RESIDUALS	2.16117
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	26.11730
DURBIN-WATSON STATISTIC	2.59723
F VALUE	43.95139
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	3.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	9.27340	0.80960
X1	10.04881	1.01849
X2	6.54767	0.42925
X3	4.15321	0.27349

CORRELATION MATRIX

	Y	X1	X2	X3
Y	1.00000	0.89529	-0.12127	0.12893
X1	0.89529	1.00000	-0.31532	0.25356
X2	-0.12127	-0.31532	1.00000	0.27005
X3	0.12893	0.25356	0.27005	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.48069	0.24703	0.19271	
B	0.07295	11.19358	1.00000	1.02724
C	0.17389	2.78639	0.98894	0.25690
D	0.26776	-2.22133	-0.96254	-0.20092

Table B-20

RECURRING MANUFACTURING LABOR HOURS FOR 100 AIRFRAMES VS WEIGHT, SPEED, TIME

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2 + D * LN X3

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-0.22987
A	0.79464
B	0.84688
C	0.55507
D	-0.53478
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.93452
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.87332
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.31793
COEFFICIENT OF VARIATION (PERCENT)	3.27976
SUM OF SQUARES OF Y RESIDUALS	2.12261
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	25.53876
DURBIN-WATSON STATISTIC	2.60290
F VALUE	48.25851
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	3.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	9.69367	0.83557
X1	10.04881	1.01849
X2	6.54767	0.42925
X3	4.15321	0.27349

CORRELATION MATRIX

	Y	X1	X2	X3
Y	1.00000	0.89798	-0.08762	0.16372
X1	0.89798	1.00000	-0.31532	0.25356
X2	-0.08762	-0.31532	1.00000	0.27005
X3	0.16372	0.25356	0.27005	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.46743	-0.15664	-0.12298	
B	0.07229	11.71428	1.00000	1.03228
C	0.17233	3.22090	0.99590	0.28515
D	0.26536	-2.01530	-0.94315	-0.17503

Table B-21

RECURRING MANUFACTURING LABOR HOURS FOR 200 AIRFRAMES VS WEIGHT, SPEED, TIME

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2 + D * LN X3

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	0.17265
A	1.18845
B	0.83062
C	0.54636
D	-0.47113
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.93786
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.87959
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.30397
COEFFICIENT OF VARIATION (PERCENT)	2.99770
SUM OF SQUARES OF Y RESIDUALS	1.94031
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	24.29084
DURBIN-WATSON STATISTIC	2.43985
F VALUE	51.13307
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	3.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	10.14000	0.81939
X1	10.04881	1.01849
X2	6.54767	0.42925
X3	4.15321	0.27349

CORRELATION MATRIX

	Y	X1	X2	X3
Y	1.00000	0.90232	-0.08180	0.18183
X1	0.90232	1.00000	-0.31532	0.25356
X2	-0.08180	-0.31532	1.00000	0.27005
X3	0.18183	0.25356	0.27005	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.40299	0.12306	0.09677	
B	0.06912	12.01704	1.00000	1.03244
C	0.16477	3.31596	0.99672	0.28621
D	0.25370	-1.85701	-0.92261	-0.15725

Table B-22

RECURRING MANUFACTURING LABOR HOURS FOR 25 AIRFRAMES VS WEIGHT, SPEED

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2 .

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-0.22825
A	0.79592
B	0.73482
C	0.25773
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.89423
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.79964
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.37706
COEFFICIENT OF VARIATION (PERCENT)	4.26375
SUM OF SQUARES OF Y RESIDUALS	3.12779
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	31.74411
DURBIN-WATSON STATISTIC	2.55514
F VALUE	43.90236
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	22.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	8.84334	0.80652
X1	10.04881	1.01849
X2	6.54767	0.42925

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.88470	-0.15544
X1	0.88470	1.00000	-0.31532
X2	-0.15544	-0.31532	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.67358	-0.13639	-0.10724	
B	0.07963	9.22777	1.00000	0.92796
C	0.18895	1.36402	0.81365	0.13717

Table B-23

RECURRING MANUFACTURING LABOR HOURS FOR 50 AIRFRAMES VS WEIGHT, SPEED

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-0.53651
A	0.58478
B	0.75648
C	0.33725
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.91123
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.83033
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.34831
COEFFICIENT OF VARIATION (PERCENT)	3.75597
SUM OF SQUARES OF Y RESIDUALS	2.66897
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	29.41340
DURBIN-WATSON STATISTIC	2.53640
F VALUE	53.83289
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	22.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	9.27340	0.80960
X1	10.04881	1.01849
X2	6.54767	0.42925

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.89529	-0.12127
X1	0.89529	1.00000	-0.31532
X2	-0.12127	-0.31532	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.54597	-0.34704	-0.26814	
B	0.07356	10.28391	1.00000	0.95167
C	0.17454	1.93225	0.93369	0.17881

Table B-24

RECURRING MANUFACTURING LABOR HOURS FOR 100 AIRFRAMES VS WEIGHT, SPEED

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-1.04113
A	0.35305
B	0.79287
C	0.42265
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.92132
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.84882
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.33933
COEFFICIENT OF VARIATION (PERCENT)	3.50053
SUM OF SQUARES OF Y RESIDUALS	2.53318
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	27.65469
DURBIN-WATSON STATISTIC	2.56989
F VALUE	61.76243
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	22.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	9.69367	0.83557
X1	10.04881	1.01849
X2	6.54767	0.42925

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.89798	-0.08762
X1	0.89798	1.00000	-0.31532
X2	-0.08762	-0.31532	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.50613	0.69127	-0.50337	
B	0.07166	11.06380	1.00000	0.966[illegible]
C	0.17004	2.48559	0.97898	0.2171[illegible]

Table B-25

RECURRING MANUFACTURING LABOR HOURS FOR 200 AIRFRAMES VS WEIGHT, SPEED

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-0.54207
A	0.58155
B	0.78303
C	0.42970
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.92726
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.85981
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.32044
COEFFICIENT OF VARIATION (PERCENT)	3.16011
SUM OF SQUARES OF Y RESIDUALS	2.25893
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	25.88412
DURBIN-WATSON STATISTIC	2.44790
F VALUE	67.46665
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	22.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	10.14000	0.81939
X1	10.04881	1.01849
X2	6.54767	0.42925

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.90232	-0.08180
X1	0.90232	1.00000	-0.31532
X2	-0.08180	-0.31532	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.42226	-0.38113	-0.29324	
B	0.06767	11.57079	1.00000	0.97330
C	0.16057	2.67603	0.98620	0.22510

Table B-26

NONRECURRING MATERIALS COST VS WEIGHT AND SPEED

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-10.63540
A	0.24049D-04
B	0.72404
C	1.92395
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.82660
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.68326
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.66487
COEFFICIENT OF VARIATION (PERCENT)	7.18399
SUM OF SQUARES OF Y RESIDUALS	9.28313
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	51.42606
DURBIN-WATSON STATISTIC	2.17561
F VALUE	22.65064
DEGREES OF FREE[illegible]BOUT REGRESSION CURVE	21.
DEGREES OF FREE[illegible]UE TO REGRESSION	2.
TOTAL DEGREES O[illegible]EDOM	23.
NUMBER OF DATA POINTS	24.

VARIABLES	MEANS	STD DEV
Y	9.25491	1.12885
X1	10.04739	1.04037
X2	6.55712	0.43581

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.43222	0.53158
X1	0.43222	1.00000	-0.31649
X2	0.53158	-0.31649	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	2.96820	-3.58311	-0.99825	
B	0.14048	5.15420	0.99996	0.66730
C	0.33535	5.73720	0.99999	0.74278

Table B-27

RECURRING MATERIALS COST FOR 25 AIRFRAMES VS WEIGHT, SPEED

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-5.34236
A	0.47846D-02
B	0.91774
C	1.00459
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.91933
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.84517
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.40120
COEFFICIENT OF VARIATION (PERCENT)	3.83647
SUM OF SQUARES OF Y RESIDUALS	3.54118
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	33.02686
DURBIN-WATSON STATISTIC	1.45026
F VALUE	60.04656
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	22.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	10.45757	0.97621
X1	10.04881	1.01849
X2	6.54767	0.42925

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.81820	0.13981
X1	0.81820	1.00000	-0.31532
X2	0.13981	-0.31532	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.78075	-3.00006	-0.99341	
B	0.08473	10.83124	1.00000	0.95749
C	0.20104	4.99688	0.99995	0.44173

Table B-28

RECURRING MATERIALS COST FOR 50 AIRFRAMES VS WEIGHT, SPEED

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-4.14315
A	0.158730-01
B	0.90023
C	0.92882
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.92567
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.85686
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.37437
COEFFICIENT OF VARIATION (PERCENT)	3.40810
SUM OF SQUARES OF Y RESIDUALS	3.08336
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	30.69236
DURBIN-WATSON STATISTIC	1.44044
F VALUE	65.84939
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	22.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	10.98469	0.94739
X1	10.04881	1.01849
X2	6.54767	0.42925

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.83509	0.11567
X1	0.83509	1.00000	-0.31532
X2	0.11567	-0.31532	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.66165	-2.49339	-0.97934	
B	0.07906	11.38606	1.00000	0.96779
C	0.18760	4.95113	0.99994	0.42083

Table B-29

RECURRING MATERIALS COST FOR 100 AIRFRAMES VS WEIGHT, SPEED

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-2.99215
A	0.501790-01
B	0.87961
C	0.86658
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.92710
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.85951
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.36098
COEFFICIENT OF VARIATION (PERCENT)	3.13324
SUM OF SQUARES OF Y RESIDUALS	2.86674
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	29.33473
DURBIN-WATSON STATISTIC	1.54069
F VALUE	67.29984
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	22.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	11.52095	0.92209
X1	10.0[illegible]381	1.01849
X2	6.54767	0.42925

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.84437	0.09705
X1	0.84437	1.00000	-0.31532
X2	0.09705	-0.31532	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.60222	-1.86750	-0.92477	
B	0.07624	11.53797	1.00000	0.97157
C	0.18089	4.79068	0.99991	0.40341

Table B-30

RECURRING MATERIALS COST FOR 200 AIRFRAMES VS WEIGHT, SPEED

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-1.89242
A	0.15071
B	0.85996
C	0.81255
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.93180
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.86826
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.33945
COEFFICIENT OF VARIATION (PERCENT)	2.81250
SUM OF SQUARES OF Y RESIDUALS	2.53504
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	27.21726
DURBIN-WATSON STATISTIC	1.46923
F VALUE	72.49595
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	22.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	12.06949	0.89541
X1	10.04881	1.01849
X2	6.54767	0.42925

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.85535	0.08108
X1	0.85535	1.00000	-0.31532
X2	0.08108	-0.31532	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.50668	-1.25602	-0.77772	
B	0.07169	11.99558	1.00000	0.97817
C	0.17010	4.77682	0.99991	0.38952

Table B-31

RECURRING MATERIALS COST FOR 25 AIRFRAMES VS WEIGHT, SPEED, TIME

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2 + D * LN X3

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-6.01261
A	0.24477D-02
B	0.87312
C	0.89519
D	0.44182
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.92597
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.85742
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.39406
COEFFICIENT OF VARIATION (PERCENT)	3.76820
SUM OF SQUARES OF Y RESIDUALS	3.26098
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	30.40097
DURBIN-WATSON STATISTIC	1.59357
F VALUE	42.09634
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	3.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	10.45757	0.97621
X1	10.04881	1.01849
X2	6.54767	0.42925
X3	4.15321	0.27349

CORRELATION MATRIX

	Y	X1	X2	X3
Y	1.00000	0.81820	0.13981	0.46105
X1	0.81820	1.00000	-0.31532	0.25356
X2	0.13981	-0.31532	1.00000	0.27005
X3	0.46105	0.25356	0.27005	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.81883	-3.30575	-0.99664	
B	0.08961	9.74387	1.00000	0.91093
C	0.21360	4.19094	0.99959	0.39362
D	0.32890	1.34330	0.80649	0.12377

Table B-32

RECURRING MATERIALS COST FOR 50 AIRFRAMES VS WEIGHT, SPEED, TIME

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2 + D * LN X3

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-4.83070
A	0.79809D-02
B	0.85445
C	0.81660
D	0.45323
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.93303
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.87055
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.36440
COEFFICIENT OF VARIATION (PERCENT)	3.31732
SUM OF SQUARES OF Y RESIDUALS	2.78849
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	28.81345
DURBIN-WATSON STATISTIC	1.68362
F VALUE	47.07545
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	3.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	10.98469	0.94739
X1	10.04881	1.01849
X2	6.54767	0.42925
X3	4.15321	0.27349

CORRELATION MATRIX

	Y	X1	X2	X3
Y	1.00000	0.83509	0.11567	0.46366
X1	0.83509	1.00000	-0.31532	0.25356
X2	0.11567	-0.31532	1.00000	0.27005
X3	0.46366	0.25356	0.27005	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.68191	-2.87215	-0.99088	
B	0.08286	10.31185	1.00000	0.91858
C	0.19752	4.13420	0.99953	[illegible].36999
D	0.30414	1.49017	0.84895	0.13083

Table B-33

RECURRING MATERIALS COST FOR 100 AIRFRAMES VS WEIGHT, SPEED, TIME

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2 + D * LN X3

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-3.69743
A	0.24787D-01
B	0.83266
C	0.75146
D	0.46491
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.93526
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.87472
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.34891
COEFFICIENT OF VARIATION (PERCENT)	3.02847
SUM OF SQUARES OF Y RESIDUALS	2.55648
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	27.82445
DURBIN-WATSON STATISTIC	1.82841
F VALUE	48.87430
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	3.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	11.52095	0.92209
X1	10.04881	1.01849
X2	6.54767	0.42925
X3	4.15321	0.27349

CORRELATION MATRIX

	Y	X1	X2	X3
Y	1.00000	0.84437	0.09705	0.46556
X1	0.84437	1.00000	-0.31532	0.25356
X2	0.09705	-0.31532	1.00000	0.27005
X3	0.46556	0.25356	0.27005	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.61042	-2.29593	-0.96793	
B	0.07934	10.49469	1.00000	0.91971
C	0.18913	3.97332	0.99931	0.34982
D	0.29122	1.59643	0.87467	0.13789

Table B-34

RECURRING MATERIALS COST FOR 200 AIRFRAMES VS WEIGHT, SPEED, TIME

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2 + D * LN X3

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	-2.61214
A	0.73377D-01
B	0.81205
C	0.69507
D	0.47443
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.94077
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.8850[illegible]
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.32459
COEFFICIENT OF VARIATION (PERCENT)	2.68898
SUM OF SQUARES OF Y RESIDUALS	2.21194
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	25.43694
DURBIN-WATSON STATISTIC	1.81648
F VALUE	53.89504
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	3.
TOTAL DEGREES OF FREEDOM	24.
NUMBER OF DATA POINTS	25.

VARIABLES	MEANS	STD DEV
Y	12.06949	0.89541
X1	10.04881	1.01849
X2	6.54767	0.42925
X3	4.15321	0.27349

CORRELATION MATRIX

	Y	X1	X2	X3
Y	1.00000	0.85535	0.08108	0.46909
X1	0.85535	1.00000	-0.31532	0.25356
X2	0.08108	-0.31532	1.00000	0.27005
X3	0.46909	0.25356	0.27005	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.49798	-1.74377	-0.90418	
B	0.07380	11.00344	1.00000	0.92367
C	0.17592	3.95103	0.99927	0.33321
D	0.27088	1.75142	0.90553	0.14490

Table B-35

FLIGHT TEST COST

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2 + D * LN X3 + E * LN X4

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

A		0.12999
LN A		-2.04033
B	X1	0.70952
C	X2	0.58563
D	X3	0.71598
E	X4	-1.55697

COEFFICIENT OF CORRELATION (UNADJUSTED)	0.90063
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.81113
STANDARD ERROR OF THE ESTIMATE (ADJUSTED)	0.44042
COEFFICIENT OF VARIATION (PERCENT)	0.04176
SUM OF SQUARES OF RESIDUALS LN	3.87944
MEAN OF ABSOLUTE PERCENT DEVIATIONS LN	2.89000
DURBIN-WATSON STATISTIC	1.90813
F VALUE	21.47350
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	20
DEGREES OF FREEDOM DUE TO REGRESSION	4
TOTAL DEGREES OF FREEDOM	24
NUMBER OF DATA POINTS	25

VARIABLES	MEANS	STD DEV
LN Y	10.54541	0.92512
LN X1	10.04881	1.01849
LN X2	6.54767	0.42925
LN X3	2.56600	0.59996
LN X4	0.13863	0.28298

CORRELATION MATRIX

LN Y	LN X1	LN X2	LN X3	LN X4
1.00000	0.29945	0.59322	0.67606	-0.21443
0.29945	1.00000	-0.31532	-0.11641	0.71801
0.59322	-0.31532	1.00000	0.60396	-0.60340
0.67606	-0.11641	0.60396	1.00000	-0.29092
-0.21443	0.71801	-0.60340	-0.29092	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	2.08660	-0.97783	-0.66016	
B	0.12982	5.46551	0.99998	0.78113
C	0.32177	1.82004	0.91625	0.27173
D	0.18933	3.78161	0.99883	0.46433
E	0.55711	-2.79474	-0.98881	-0.47625

Table B-36

TOTAL COST FOR 25 AIRCRAFT

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	0.49547
A	1.64127
B	0.72594
C	0.80384
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.93317
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.87081
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.28757
COEFFICIENT OF VARIATION (PERCENT)	2.19859
SUM OF SQUARES OF Y RESIDUALS	1.73662
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	22.63131
DURBIN-WATSON STATISTIC	2.58896
F VALUE	70.77542
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	23.
NUMBER OF DATA POINTS	24.

VARIABLES	MEANS	STD DEV
Y	13.07974	0.76449
X1	10.07749	1.03004
X2	6.55430	0.43717

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.82619	0.13644
X1	0.82619	1.00000	-0.33046
X2	0.13644	-0.33046	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.29937	0.38132	0.29320	
B	0.06168	11.76965	1.00000	0.97809
C	0.14533	5.53132	0.99998	0.45967

Table B-37

TOTAL COST FOR 50 AIRCRAFT

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	1.03687
A	2.82037
B	0.72595
C	0.76171
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.93475
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.87375
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.28282
COEFFICIENT OF VARIATION (PERCENT)	2.11927
SUM OF SQUARES OF Y RESIDUALS	1.67971
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	21.53550
DURBIN-WATSON STATISTIC	2.56559
F VALUE	72.67081
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	23.
NUMBER OF DATA POINTS	24.

VARIABLES	MEANS	STD DEV
Y	13.34507	0.76058
X1	10.07749	1.03004
X2	6.55430	0.43717

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.83845	0.11293
X1	0.83845	1.00000	-0.33046
X2	0.11293	-0.33046	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.27790	0.81138	0.57375	
B	0.06066	11.96746	1.00000	0.98313
C	0.14292	5.32949	0.99997	0.43782

Table B-38

TOTAL COST FOR 100 AIRCRAFT

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	1.45697
A	4.29292
B	0.72760
C	0.73718
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.93963
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.88290
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.27108
COEFFICIENT OF VARIATION (PERCENT)	1.99018
SUM OF SQUARES OF Y RESIDUALS	1.54322
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	20.34147
DURBIN-WATSON STATISTIC	2.47067
F VALUE	79.17026
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	23.
NUMBER OF DATA POINTS	24.

VARIABLES	MEANS	STD DEV
Y	13.62106	0.75697
X1	10.07749	1.03004
X2	6.55430	0.43717

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.84938	0.09856
X1	0.84938	1.00000	-0.33046
X2	0.09856	-0.33046	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.22488	1.18948	0.75247	
B	0.05814	12.51393	1.00000	0.99007
C	0.13699	5.38111	0.99998	0.42574

Table B-39

TOTAL COST FOR 200 AIRCRAFT

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	1.98574
A	7.28446
B	0.73668
C	0.68932
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.94688
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.89657
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.25520
COEFFICIENT OF VARIATION (PERCENT)	1.83232
SUM OF SQUARES OF Y RESIDUALS	1.36766
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	19.29745
DURBIN-WATSON STATISTIC	2.38318
F VALUE	91.02095
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	21.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	23.
NUMBER OF DATA POINTS	24.

VARIABLES	MEANS	STD DEV
Y	13.92767	0.75824
X1	10.07749	1.03004
X2	6.55430	0.43717

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.86941	0.06672
X1	0.86941	1.00000	-0.33046
X2	0.06672	-0.33046	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.15311	1.72208	0.90025	
B	0.05474	13.45875	1.00000	1.00074
C	0.12897	5.34497	0.99997	0.39743

Table B-40

TOTAL COST FOR 100 AIRFRAMES--DIFFICULTY INDEX

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2 + D * LN X3

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	2.03995
A	7.69021
B	0.69396
C	0.63295
D	0.37275
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.94399
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.89111
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.31718
COEFFICIENT OF VARIATION (PERCENT)	2.28870
SUM OF SQUARES OF Y RESIDUALS	0.90541
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	22.06449
DURBIN-WATSON STATISTIC	2.26368
F VALUE	24.55027
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	9.
DEGREES OF FREEDOM DUE TO REGRESSION	3.
TOTAL DEGREES OF FREEDOM	12.
NUMBER OF DATA POINTS	13.

VARIABLES	MEANS	STD DEV
Y	13.85835	0.83240
X1	10.28659	1.15731
X2	6.71468	0.39340
X3	1.15316	0.47490

CORRELATION MATRIX

	Y	X1	X2	X3
Y	1.00000	0.85175	-0.16627	0.55985
X1	0.85175	1.00000	-0.55811	0.25332
X2	-0.16627	-0.55811	1.00000	0.34359
X3	0.55985	0.25332	0.34359	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	3.14618	0.64839	0.46707	
B	0.11616	5.97435	0.99979	0.96483
C	0.35199	1.79818	0.89431	0.29914
D	0.25011	1.49035	0.82968	0.21266

Table B-41

TOTAL COST FOR 100 AIRFRAMES--GROUP 1

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	7.65322
A	2107.42485
B	0.58218
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.79480
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.63170
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.28995
COEFFICIENT OF VARIATION (PERCENT)	2.20775
SUM OF SQUARES OF Y RESIDUALS	0.58848
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	17.82334
DURBIN-WATSON STATISTIC	2.36527
F VALUE	12.00643
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	7.
DEGREES OF FREEDOM DUE TO REGRESSION	1.
TOTAL DEGREES OF FREEDOM	8.
NUMBER OF DATA POINTS	9.

VARIABLES	MEANS	STD DEV
Y	13.13309	0.44691
X1	9.41259	0.61012

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.58443	4.83028	0.99810	
B	0.16802	3.46503	0.98952	0.79480

Table B-42

TOTAL COST FOR 100 AIRFRAMES--GROUP 2

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	2.34432
A	10.42618
B	1.16458
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.96559
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.93237
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.16053
COEFFICIENT OF VARIATION (PERCENT)	1.15653
SUM OF SQUARES OF Y RESIDUALS	0.15463
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	11.91005
DURBIN-WATSON STATISTIC	2.29148
F VALUE	82.71455
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	6.
DEGREES OF FREEDOM DUE TO REGRESSION	1.
TOTAL DEGREES OF FREEDOM	7.
NUMBER OF DATA POINTS	8.

VARIABLES	MEANS	STD DEV
Y	13.88062	0.57150
X1	9.90594	0.47385

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.26973	1.84632	0.88563	
B	0.12805	9.09475	0.99990	0.96559

Table B-43

TOTAL COST FOR 100 AIRFRAMES--GROUP 3

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	3.18462
A	24.15820
B	0.96224
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.95118
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.90474
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.21467
COEFFICIENT OF VARIATION (PERCENT)	1.50569
SUM OF SQUARES OF Y RESIDUALS	0.18433
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	15.51110
DURBIN-WATSON STATISTIC	2.49002
F VALUE	37.98869
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	4.
DEGREES OF FREEDOM DUE TO REGRESSION	1.
TOTAL DEGREES OF FREEDOM	5.
NUMBER OF DATA POINTS	6.

VARIABLES	MEANS	STD DEV
Y	14.25702	0.62208
X1	11.50691	0.61493

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	1.79858	1.77063	0.84867	
B	0.15612	6.16350	0.99648	0.95118

Table B-44

REGRESSION EQUATIONS FOR GROUP 1 AIRCRAFT--100 UNITS

Nonrecurring manufacturing hours

R^2 = .07
SEE(%) = +156, -61
F = .55

$ML_{NR} = 26.4(Wt)^{.4}$

Nonrecurring manufacturing materials

R^2 = .10
SEE(%) = +186, -65
F = .67

$MM_{NR} = 33.9(Wt)^{.55}$

Engineering hours

R^2 = .27
SEE(%) = +38, -27
F = 1.10

$E_{100} = .02(Wt)^{.31}(Speed)^{1.43}$

Tooling hours

R^2 = .37
SEE(%) = +52, -34
F = 4.04

$T_{100} = 53(Wt)^{.49}$

Manufacturing hours

R^2 = .79
SEE(%) = +39, -28
F = 25.8

$ML_{100} = 1.07(Wt)^{.98}$

Manufacturing materials

R^2 = .59
SEE(%) = +22, -18
F = 10.2

$MM_{100} = 1588.4(Wt)^{.37}$

Flight Test

R^2 = .51
SEE(%) = +60, -37
F = 7.2

$FT = 3739(N)^{.6}$

Table B-45

RECRESSION EQUATIONS FOR GROUP 2 AIRCRAFT--100 UNITS

Nonrecurring manufacturing hours

R^2 = .74
SEE(%) = +60, -37
F = 17.2

$$ML_{NR} = .00069(Wt)^{1.54}$$

Nonrecurring manufacturing material

R^2 = .62
SEE(%) = +68, -41
F = 9.9

$$MM_{NR} = .063(Wt)^{1.30}$$

Engineering hours

R^2 = .92
SEE(%) = +22, -18
F = 66.0

$$E_{100} = .03(Wt)^{1.30}$$

Tooling hours

R^2 = .59
SEE(%) = +45, -31
F = 8.6

$$T_{100} = 1.54(Wt)^{.87}$$

Manufacturing hours

R^2 = .83
SEE(%) = +30, -23
F = 29.0

$$ML_{100} = .28(Wt)^{1.12}$$

Manufacturing materials

R^2 = .81
SEE(%) = +40, -29
F = 25.5

$$MM_{100} = .17(Wt)^{1.38}$$

Flight Test

R^2 = .74
SEE(%) = +52, -34
F = 7.2

$$FT = .098(Wt)^{1.16}(N)^{.73}$$

Table B-46

REGRESSION EQUATIONS FOR GROUP 3 AIRCRAFT--100 UNITS

Nonrecurring manufacturing hours

R^2 = .65
SEE(%) = +57, -36
F = 7.5

$$ML_{NR} = .087(Wt)^{.89}$$

Nonrecurring manufacturing material

R^2 = .40
SEE(%) = 114, -53
F = 2.7

$$MM_{NR} = .36(Wt)^{.91}$$

Engineering hours

R^2 = .82
SEE(%) = +39, -28
F = 18.6

$$E_{100} = .095(Wt)^{1.02}$$

Tooling hours

R^2 = .63
SEE(%) = +40, -29
F = 6.7

$$T_{100} = 9.14(Wt)^{.64}$$

Manufacturing hours

R^2 = .92
SEE(%) = +20, -16
F = 46.9

$$ML_{100} = 1.16(Wt)^{.90}$$

Manufacturing materials

R^2 = .81
SEE(%) = +54, -35
F = 17.1

$$MM_{100} = .079(Wt)^{1.30}$$

Flight Test

R^2 = .39
SEE(%) = +156, -61
F = .95

$$FT = .76(Wt)^{.74}(N)^{1.00}$$

Table B-47

TOTAL COST--PROTOTYPE PROGRAMS

LOG-LINEAR REGRESSION -- LN Y = LN A + B * LN X1 + C * LN X2

SUMMARY TABLE

NOTE -- STATISTICS ARE BASED ON LOGARITHMS

LN A	7.01699
A	1115.42508
B	0.35300
C	0.98644
COEFFICIENT OF CORRELATION (UNADJUSTED)	0.86476
COEFFICIENT OF DETERMINATION (UNADJUSTED)	0.74782
STANDARD ERROR OF THE ESTIMATE OF Y (ADJUSTED)	0.30666
COEFFICIENT OF VARIATION (PERCENT)	2.77849
SUM OF SQUARES OF Y RESIDUALS	0.65830
MEAN OF ABSOLUTE ACTUAL PERCENT Y DEVIATIONS	21.47897
DURBIN-WATSON STATISTIC	2.46315
F VALUE	10.37881
DEGREES OF FREEDOM ABOUT REGRESSION CURVE	7.
DEGREES OF FREEDOM DUE TO REGRESSION	2.
TOTAL DEGREES OF FREEDOM	9.
NUMBER OF DATA POINTS	10.

VARIABLES	MEANS	STD DEV
Y	11.03711	0.53856
X1	9.72548	1.10835
X2	0.59506	0.33815

CORRELATION MATRIX

	Y	X1	X2
Y	1.00000	0.61390	0.48732
X1	0.61390	1.00000	-0.18175
X2	0.48732	-0.18175	1.00000

PARAMETERS	STD ERROR	T-RATIO	LEVEL SIGNIF	BETA COEFF
LN A	0.96724	7.25462	0.99983	
B	0.09379	3.76373	0.99296	0.72648
C	0.30742	3.20879	0.98512	0.61936

Appendix C

USING ESTIMATING EQUATIONS

The preceding sections present a number of equations for estimating both the major elements of cost--engineering hours, tooling hours, etc.--and total cost as a function of such variables as weight, speed, and time. Estimates resulting from those equations can vary enormously, depending on the size and composition of the sample and on the explanatory variables chosen. In view of such differences, it is natural to ask under what circumstances those parametric equations can be relied on for useful estimates.

There is no simple answer to that question. Disclaimers on pp. iii and 53 point out that the equations are intended for use only in advanced planning activities when better information is not available. Disclaimers of that type are often ignored, however, and parametric models may be used in all phases of system acquisition. If, in fact, an airframe model is suitable only for long-range planning studies, misuse is inevitable.

Another kind of misuse may also occur: the precision implied by a mathematical model may inhibit the use of judgment. Logically, that attitude is indefensible because, as the following pages will show, opponents in the adversary procedure that characterizes system acquisitions can find models to justify almost any set of numbers. Judgment is required in choosing a model representative of the aircraft whose cost is to be estimated; and since no model can be completely representative, judgment is required in interpreting the estimates obtained.

A previous Rand report, *Cost-Estimating Relationships for Aircraft Airframes*,[1] discusses statistical variations in predictions obtained from models having a number of regression relationships. The intent of this appendix is to show graphically the implications of changing the composition of the sample and of choosing different independent variables.

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[1]G. S. Levenson et al., R-761-PR, December 1971, pp. 35-52.

By graphing the results of the equations, it is possible to examine cost trends and to show visually where extrapolation will lead. The relative importance of the individual cost elements should be appreciated, and the advantage or disadvantages of highly aggregated models compared with more detailed models should be explored. Only when an estimating model is thoroughly understood can it be used effectively.

ENGINEERING HOURS

Figures C-1 and C-2 show curves based on equations from preceding sections that are repeated here for convenience:

	Equation	Sample[2]
1.	$E_{100} = .00081\ W^{.672} S^{.991} T^{.648}$	24 aircraft--all types
2.	$E_{100} = .00162\ W^{.751} S^{1.175}$	24 aircraft--all types
3.	$E_{100} = .02344\ W^{.656} S^{.960}$	9 newer aircraft--all types
4.	$E_{100} = .02\ W^{.31} S^{1.43}$	Group 1 (9 small, slow aircraft)
5.	$E_{100} = .03\ W^{1.3}$	Group 2 (8 small, fast aircraft)
6.	$E_{100} = .095\ W^{1.02}$	Group 3 (6 large, slow aircraft)

where E_{100} = cumulative total engineering hours for 100 units (thousands),

W = airframe unit weight (lb),

S = maximum speed at best altitude (kn),

T = number of quarters after 1942 in which first flight of a production aircraft occurs.[3]

The curves suggest the problem encountered in using parametric estimating techniques. Estimates for a 100,000-lb aircraft with a maximum speed of 550 kn and a production aircraft flight date of December 1975 range from 12 million to 23 million engineering hours. If the flight date is advanced to the end of 1980, the range is 12 to 25 million.

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[2]Aircraft in each sample are identified in Table C-1.

[3]The symbols W, S, and T are used throughout this appendix. In subsequent equations, only symbols not previously used will be defined.

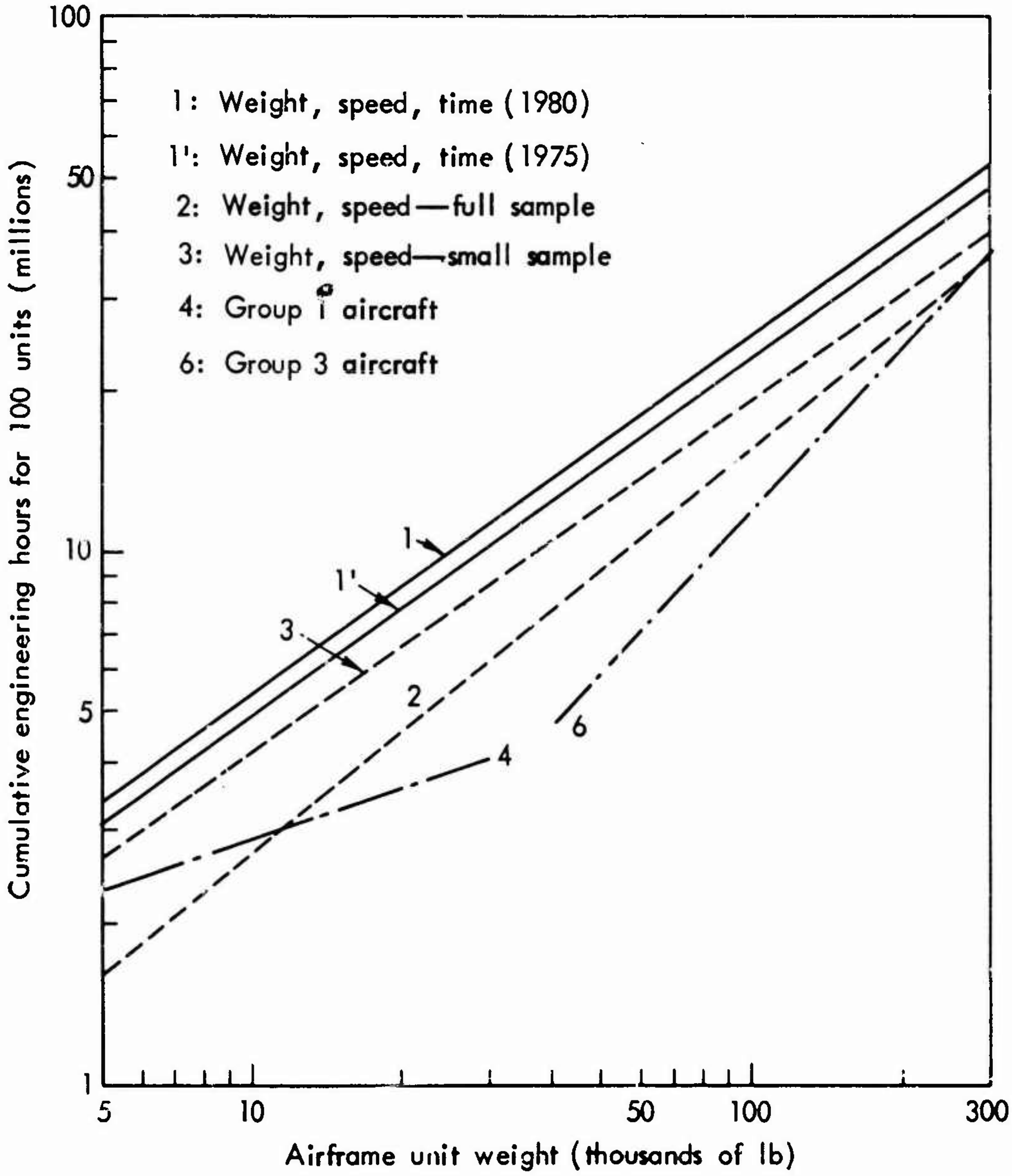

Fig. C-1—Cumulative engineering hours -- 550 kn

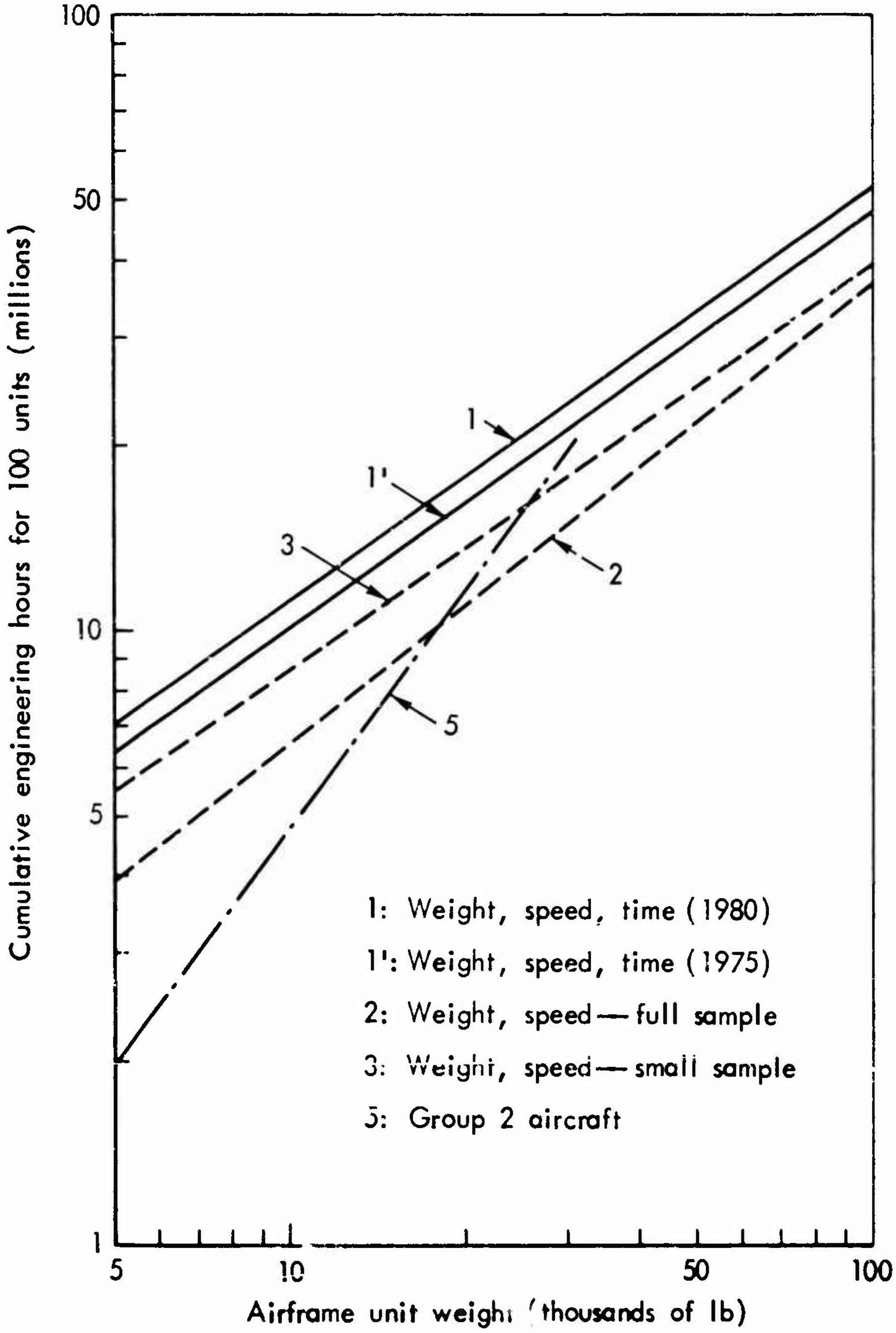

Fig. C-2 — Cumulative engineering hours -- 1150 kn

For a 30,000-lb, 1150-kn aircraft, the range is about 15 to 23 million, again a very substantial difference.

For the reasons discussed in Section III, we believe that the preferred equation for estimating engineering hours for future military aircraft is Eq. 3. However, as Table C-1 shows, Eq. 3 badly overestimates the engineering hours required for the A-5 and C-141 at 100 units, and badly underestimates them for the B-58. We shall not attempt after-the-fact rationalizations of those discrepancies, but in looking at estimates based on the equations shown throughout this report, it is essential to keep one fact in mind: comparisons at the cost-element level can be unreliable because of differences in definitions, in accounting procedures, and in reporting practices among companies and among programs within the same company. Although engineering, tooling, manufacturing labor, etc., are carefully defined in the Contractor Cost Data Report (CCDR), and prior to that in the Cost Information Report (CIR) required of all contractors on military aircraft programs since 1967, inconsistencies in the hours and dollars reported still exist. Industrial engineering hours may be reported as engineering, tooling, or manufacturing hours. Purchased engineering should be converted to engineering hours, but it may be recorded as a material cost. Production control may be categorized as either tooling or manufacturing. Certain management functions are treated as indirect costs by one contractor and as direct costs by another. And the differences are not trivial. When queried on this subject, contractors stated that choice of one category rather than another could perturb the results by as much as 20 percent.

TOOLING HOURS

The equation given in Section IV, p. 23, for cumulative tooling hours is shown below as Eq. 1. Equations 2, 3, and 4 are taken from Appendix B, pp. 108-110.

Table C-1

Y-DEVIATIONS FOR SIX ENGINEERING-HOUR EQUATIONS[a]

Aircraft	Percent of Y-Deviation: Cumulative Engineering Hours at 100 Units					
	Eq. 1	Eq. 2	Eq. 3	Eq. 4	Eq. 5	Eq. 6
A-3	-43	-65		-22		
A-4	13	15		-25		
A-5	-3	-8	-33		-26	
A-6	19	32	-1	41		
B-52	1	-23				0
B-58	45	39	27		15	
RB-66	-49	-71		-13		
C-130	43	43				33
C-133	13	7				-42
KC-135	-70	-80				-35
C-141	-25	-7	-37			4
C-5A	14	31	19			19
F-3	13	1		5		
F-4	2	2	-23		10	
F-6	16	12		-4		
F-100	-19	-36		-44		
F-102	20	17		14		
F-104	-20	-29			17	
F-105	3	-11			-11	
F-106	-38	-50			-34	
F-111	9	24	11		4	
F-14	-14	13	-2		12	
T-38	37	46	17	18		
T-39	-89	-43				
Absolute mean	26	29	19	21	16	22

[a]Percent deviation = $\frac{\text{Observed Y-Calculated Y}}{\text{Observed Y}}$.

	Equation	Sample
1.	$T_{100} = .472\ W^{.638} S^{.499}$	24 aircraft--all types
2.	$T_{100} = 53\ W^{.49}$	Group 1
3.	$T_{100} = 1.54\ W^{.87}$	Group 2
4.	$T_{100} = 9.14\ W^{.64}$	Group 3

where T_{100} = cumulative total tooling hours at 100 units (thousands).

It will be noticed immediately that an important independent variable--production rate--is missing; and since tooling hours are to some extent a function of production rate, the validity of the equations may be questioned. The reasons why rate is not a statistically significant variable were discussed earlier in this report. The problem is mentioned here because production rate helps to determine the point at which all initial tooling hours have been incurred and that, in turn, influences the slope of the cost-quantity curve. Where the planned production rate is low--say, 4 aircraft per month--all nonrecurring tooling hours will have been expended by the time about 20 aircraft have been produced. The cumulative-tooling-hours curve will be relatively flat thereafter, as only recurring tooling hours are incurred. Curve A in Fig. C-3 is an example of that kind of program. Curves B and C are examples of programs where the planned production rates were higher, and nonrecurring tooling hours continued to be expended until substantially more aircraft had been produced.

The stability in the relationship among the curves should be reasonably good from 100 units on, and information from industry confirms their utility. What about estimates for smaller quantities? The potential for error is probably greater at 50 units than at 100, and greater at 25 units than at 50, when the equations given above are used. The sample is large enough, however, for a lot of the variability seen in Fig. C-3 to wash out. Figure C-4 shows scaling curves plotted for four production quantities. Ideally, all four would be parallel, but the curves for 25 and 50 units are perceptibly steeper than the others. They are not so different, however, that a crossover occurs within the range of airframe unit weights in the sample.

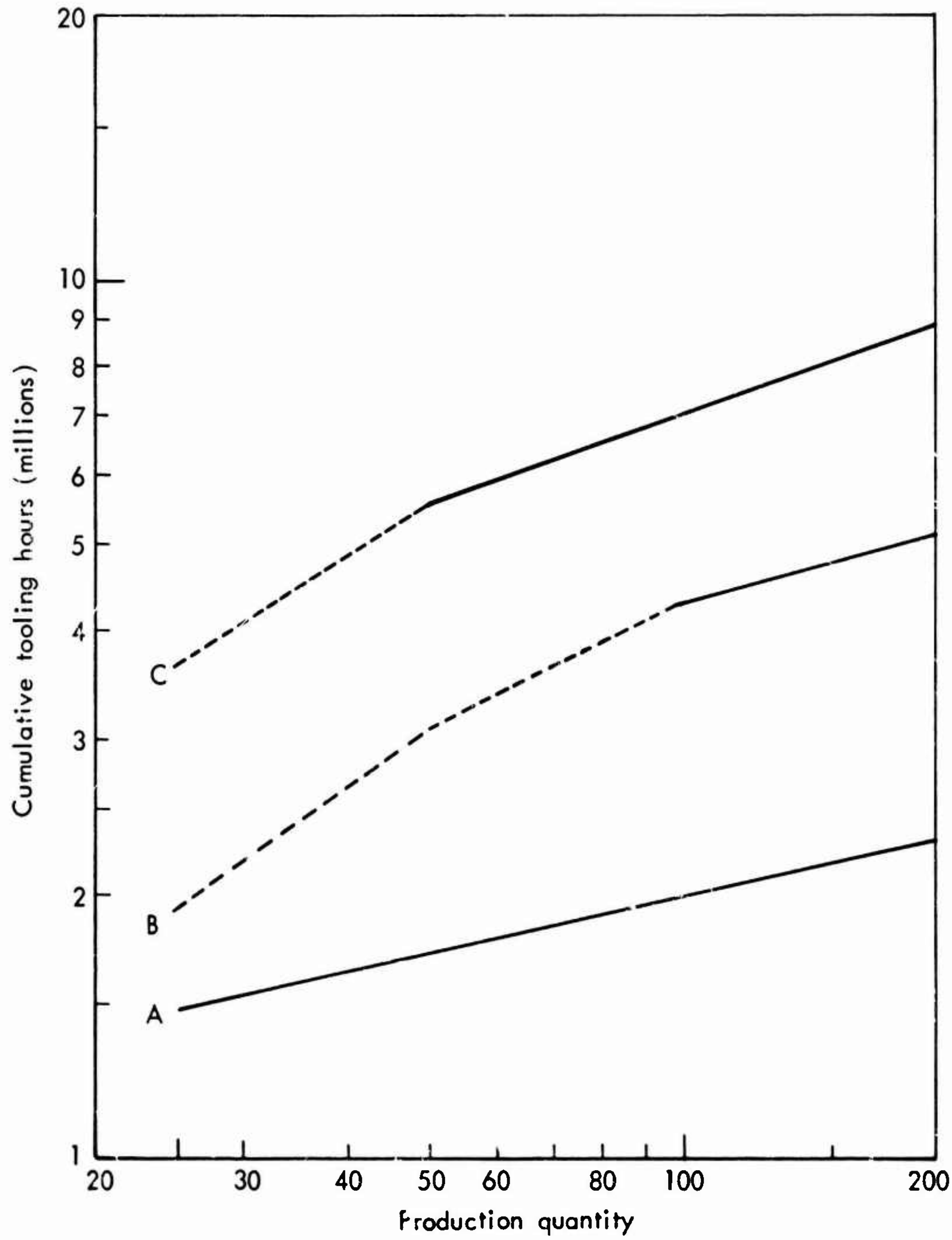

Fig. C-3 — Cumulative tooling hours for three airframe programs

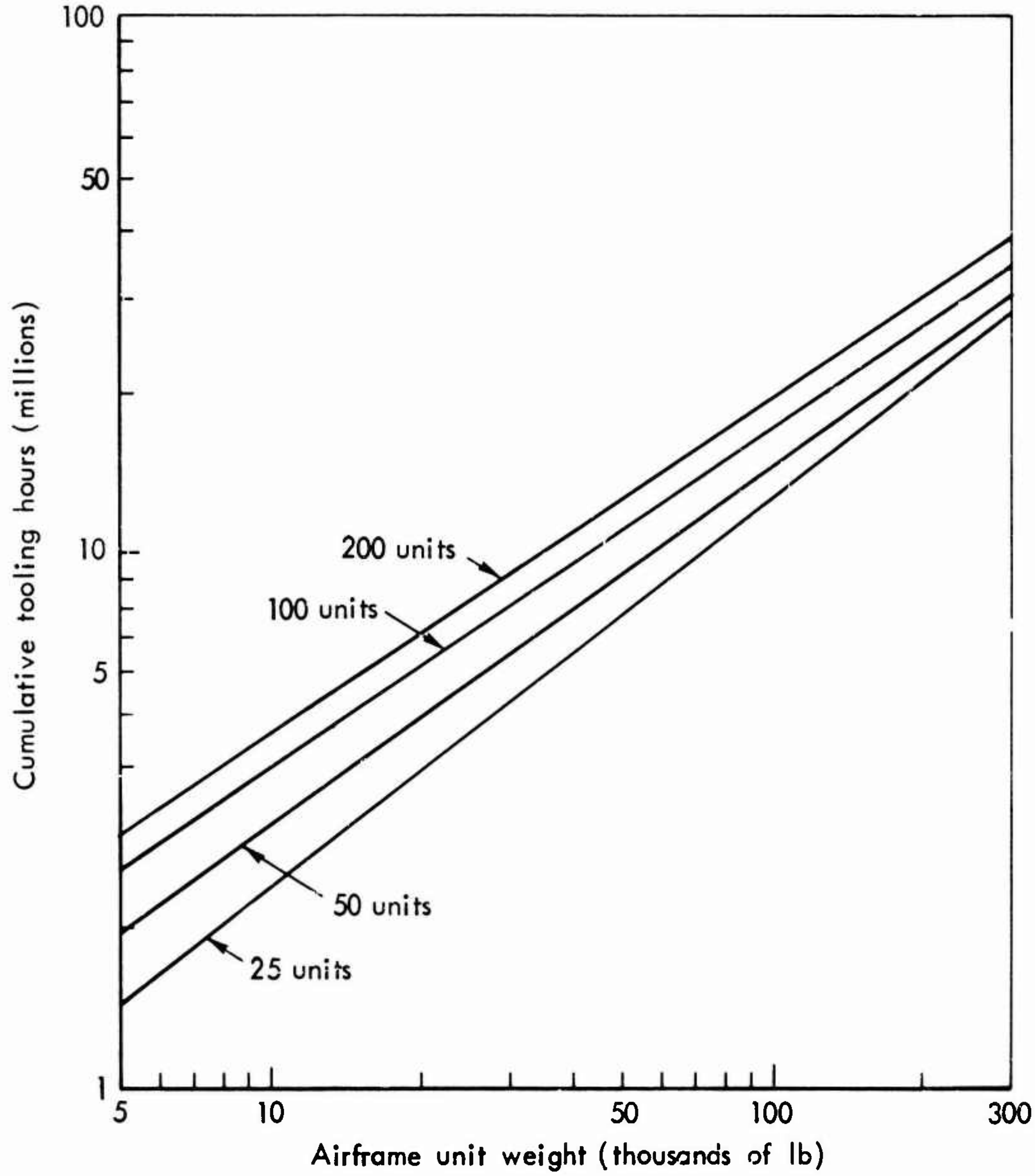

Fig. C-4—Cumulative tooling hours for four production quantities -- 550 kn

In addition to the question about production rate being used as an explanatory variable, there is the ever-present question about the desirability of working with smaller but more homogeneous samples, e.g., Groups 1, 2, and 3 mentioned earlier. Figure C-5 illustrates the results of one effort to use stratified samples. Curves 1 and 1' are based on the entire sample; the other three curves are based on the groups described under "Engineering Hours," above. The crossover of Curves 2 and 3 says that Mach 2 aircraft require fewer tooling hours than Mach .84 aircraft when the airframe unit weight is below 10,500 lb but more hours when the weight is greater. Such a conclusion is illogical of course and must be rejected.

Curve 4 (Group 3 aircraft) lends some credence to the notion that cargo aircraft are enough different to be treated as a separate class. That can be done either by creating only a small sample of cargoes or by incorporating a dummy variable in the estimating equation as shown below:

$$T_{100} = .522\ W^{.69} S^{.41} DV^{-.322}$$

where DV = dummy variable (DV = 1 for all types of aircraft except cargo. DV = 2 for cargoes). The effect of both on Y-deviations is shown below:

Aircraft	Percent of Y-Deviation		
	Total Sample	Dummy Variable	Cargo Only
C-5	-2	0	4
C-130	12	18	-1
C-133	-15	-11	-36
KC-135	16	24	24
C-141	-55	-45	-45
Absolute mean	20	20	22

By using a dummy variable, two estimates are improved, two are degraded, one remains essentially the same, and the absolute mean is unchanged.

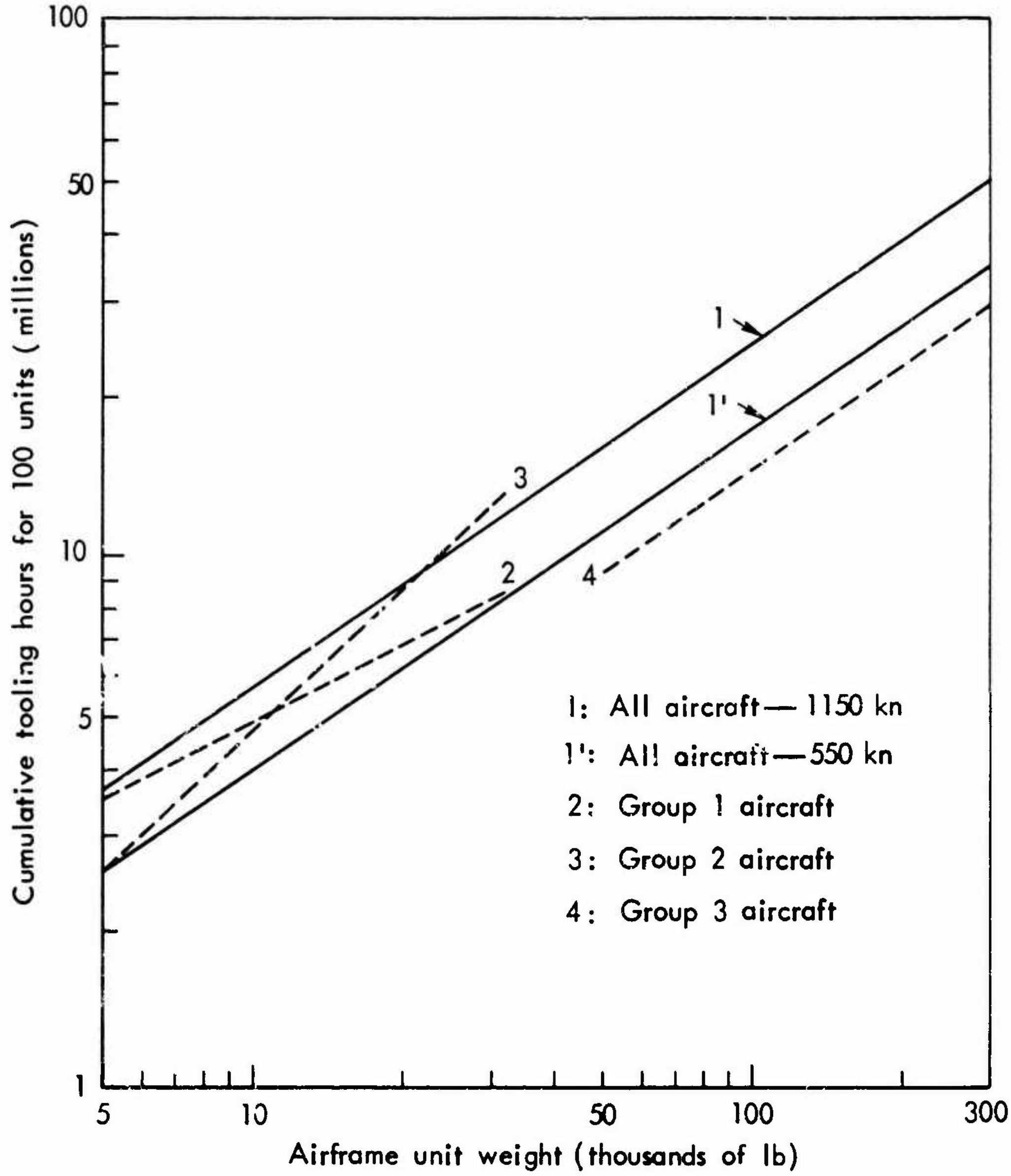

Fig. C-5—Cumulative tooling hours (100 units)

When cargo aircraft are treated as a separate sample, the results are worse. Thus there is no persuasive reason to consider cargo aircraft as a distinct group insofar as tooling is concerned.

MANUFACTURING HOURS

Nonrecurring Hours

No potentially useful estimating equations for nonrecurring manufacturing hours were found except Eq. 1 below:

	Equation	Sample
1.	$ML_{NR} = .000626\ W^{.688} S^{1.21}$	24 aircraft
2.	$ML_{NR} = .00069\ W^{1.54}$	Group 2
3.	$ML_{NR} = .087\ W^{.89}$	Group 3

where ML_{NR} = nonrecurring manufacturing hours (thousands).

Figure C-6 shows curves based on Eq. 1 for two speeds--550 and 1150 kn--and curves for Groups 2 and 3 (the regression equation for Group 1 had such poor statistical properties, e.g., $R^2 = .07$, that it is not shown). The slope of the Group 2 curve is too steep to be credible; it makes small airframes too cheap and large airframes too expensive. Group 3 aircraft are again below the total sample, but that is because all but one of those aircraft have speeds below 550 kn. The scaling curves shown for the total sample appear to be representative of the nonrecurring manufacturing hours in a normal airframe development program.

Recurring Hours

In an aircraft production program, manufacturing labor is the largest of the direct-cost elements; hence it is usually scrutinized more carefully than the others. Unfortunately, the two best estimating equations presented in Section V for manufacturing labor (Eqs. 1 and 2, below) give rather different results, because one incorporates a time variable and the other does not:

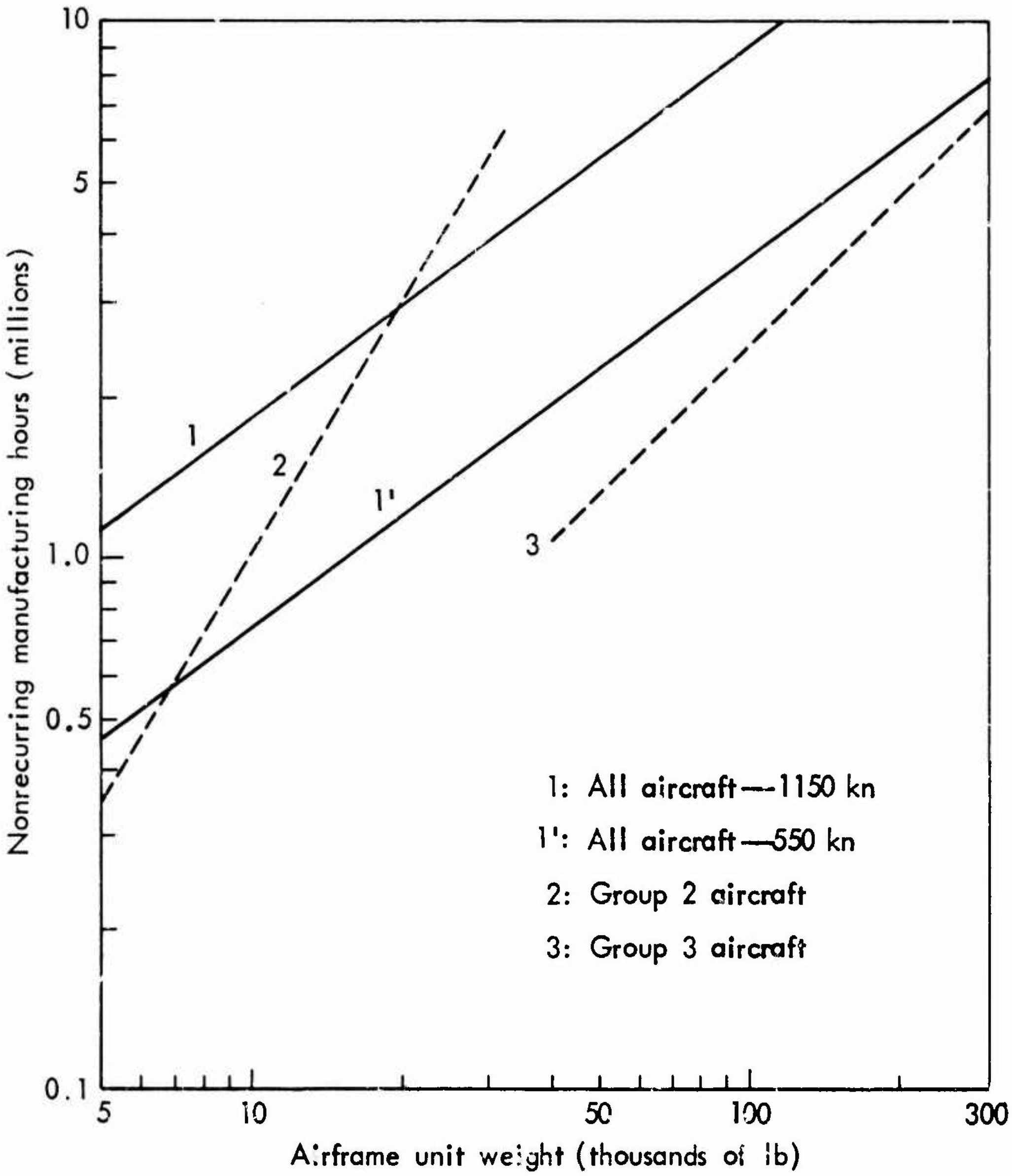

Fig. C-6—Nonrecurring manfacturing hours

Equation	Sample
1. $M_{100} = .353\ W^{.793} S^{.423}$	24 aircraft--all types
2. $M_{100} = .795\ W^{.847} S^{.555} T^{-.535}$	24 aircraft--all types
3. $M_{100} = 1.07\ W^{.98}$	Group 1
4. $M_{100} = .28\ W^{1.12}$	Group 2
5. $M_{100} = 1.16\ W^{.90}$	Group 3

where M_{100} = cumulative recurring manufacturing hours at 100 units (thousands).

The difference is shown in Figs. C-7 and C-8 in cumulative total hours and in Figs. C-9 and C-10 in unit hours per pound. (The conversion to unit hours assumed a cost-quantity curve slope of 77 percent.) For a 50,000-lb airframe and a speed of 550 kn, Eq. 1 gives a value 46 percent higher than Eq. 2 when the time is 1975, and 58 percent higher when the time is 1980. The differences are not so great for higher-speed aircraft but they are sizable enough to be disturbing. Should one assume that improvements in manufacturing techniques have reduced hours to the extent indicated, or should one take a more conservative view and argue that while some reduction has occurred, it is less dramatic than Eq. 2 suggests? One way to compare the two equations is to ask which one does a better job of estimating manufacturing hours for recent aircraft. On the basis of the curves in Figs. C-7 to C-10, we would expect the weight-speed equation to give consistently higher estimates than the weight-speed-time equation. As shown by the Y-deviations below, the difference for the three most recent aircraft--the F-111, C-5, and F-14--ranges from 16 to 20 percent. In every case, the equation with a time variable underestimates manufacturing hours. In two cases, the weight-speed equation overestimates hours. One might be inclined to say that the truth lies somewhere in between, but the

	Percent of Y-deviation	
Aircraft	Weight, Speed	Weight, Speed, Time
F-111	-11	5
C-5	0	17
F-14	-4	16

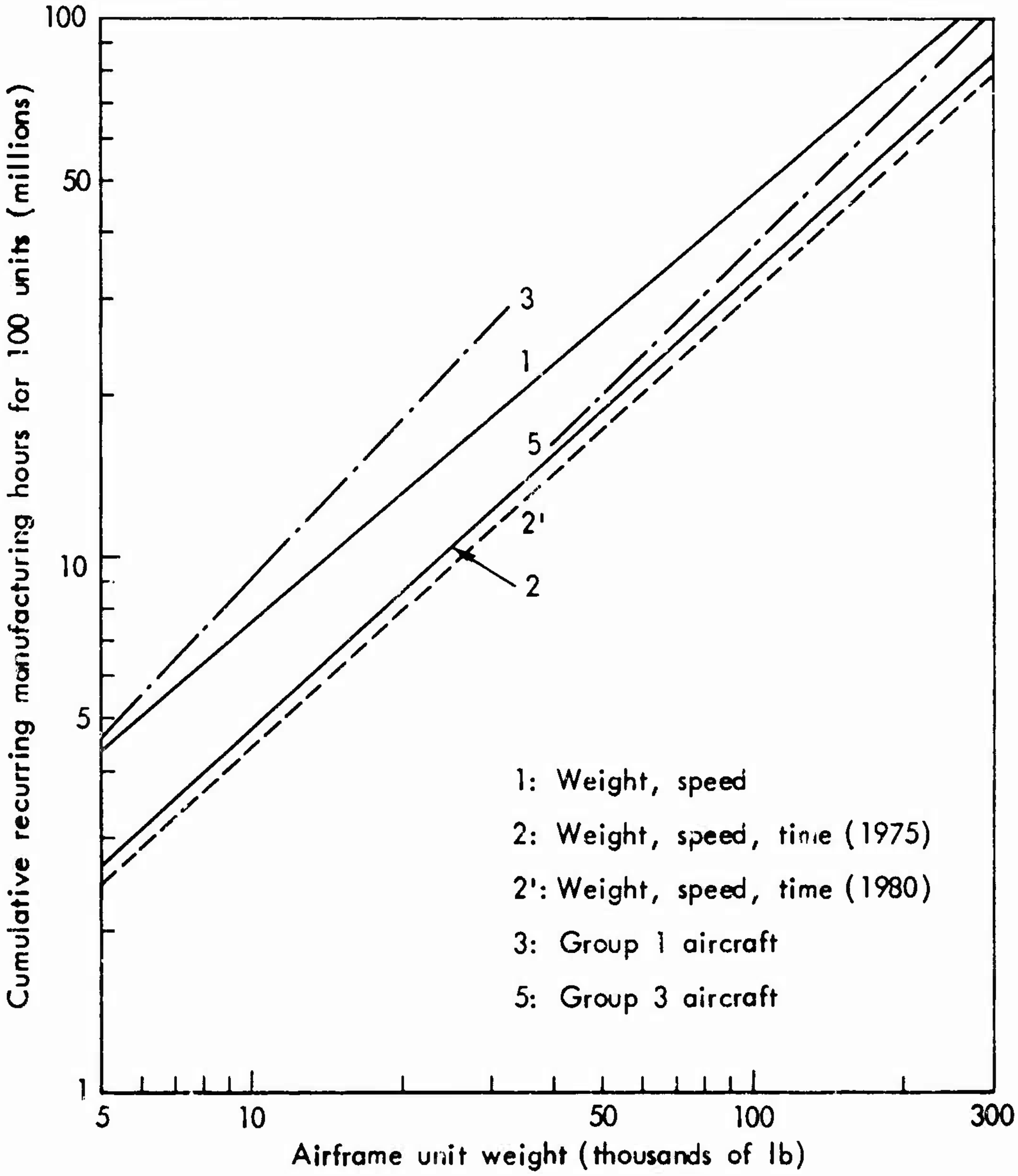

Fig. C-7 — Cumulative recurring manufacturing hours -- 550 kn

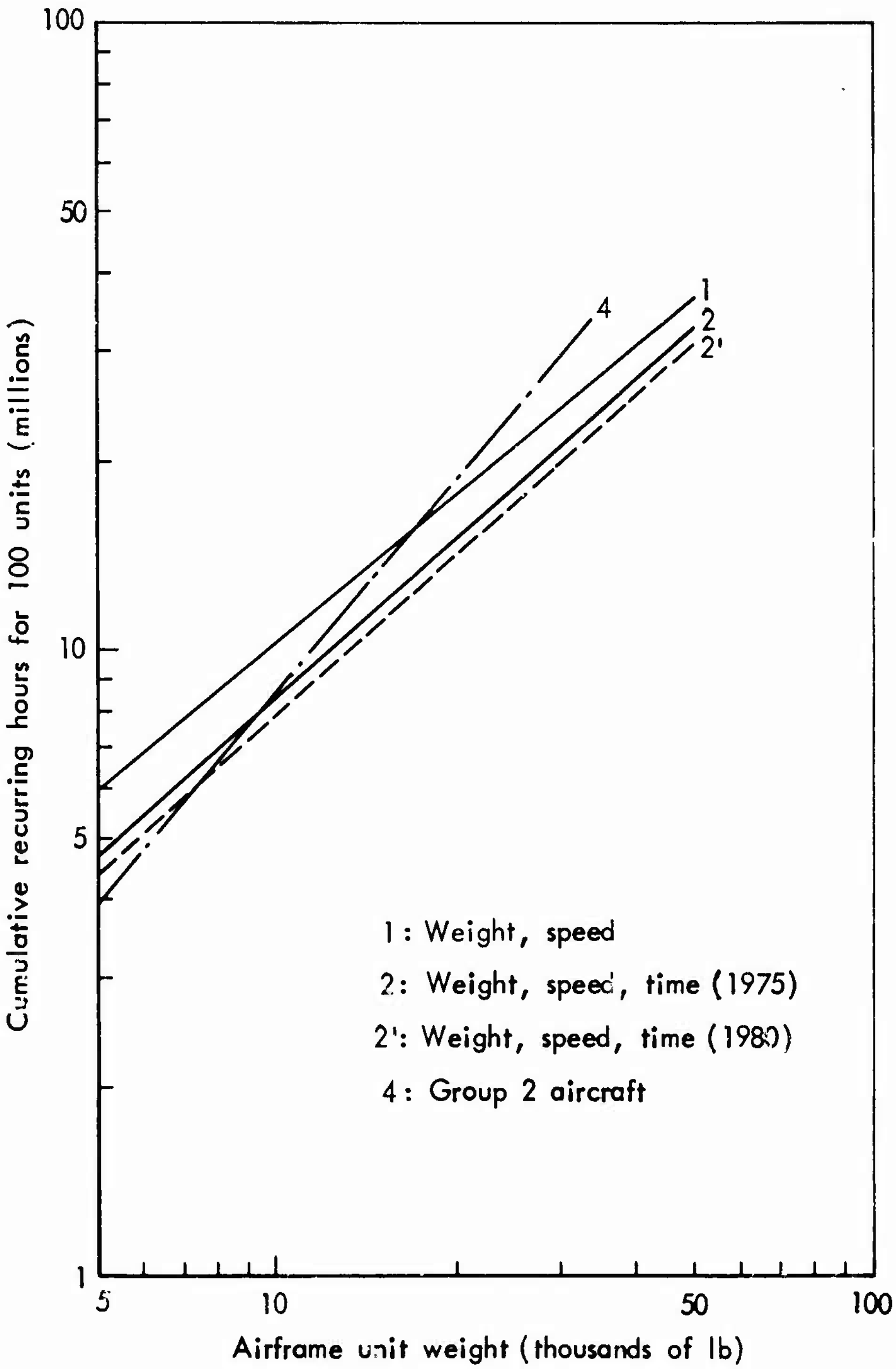

Fig. C-8—Cumulative recurring manufacturing hours -- 1150 kn

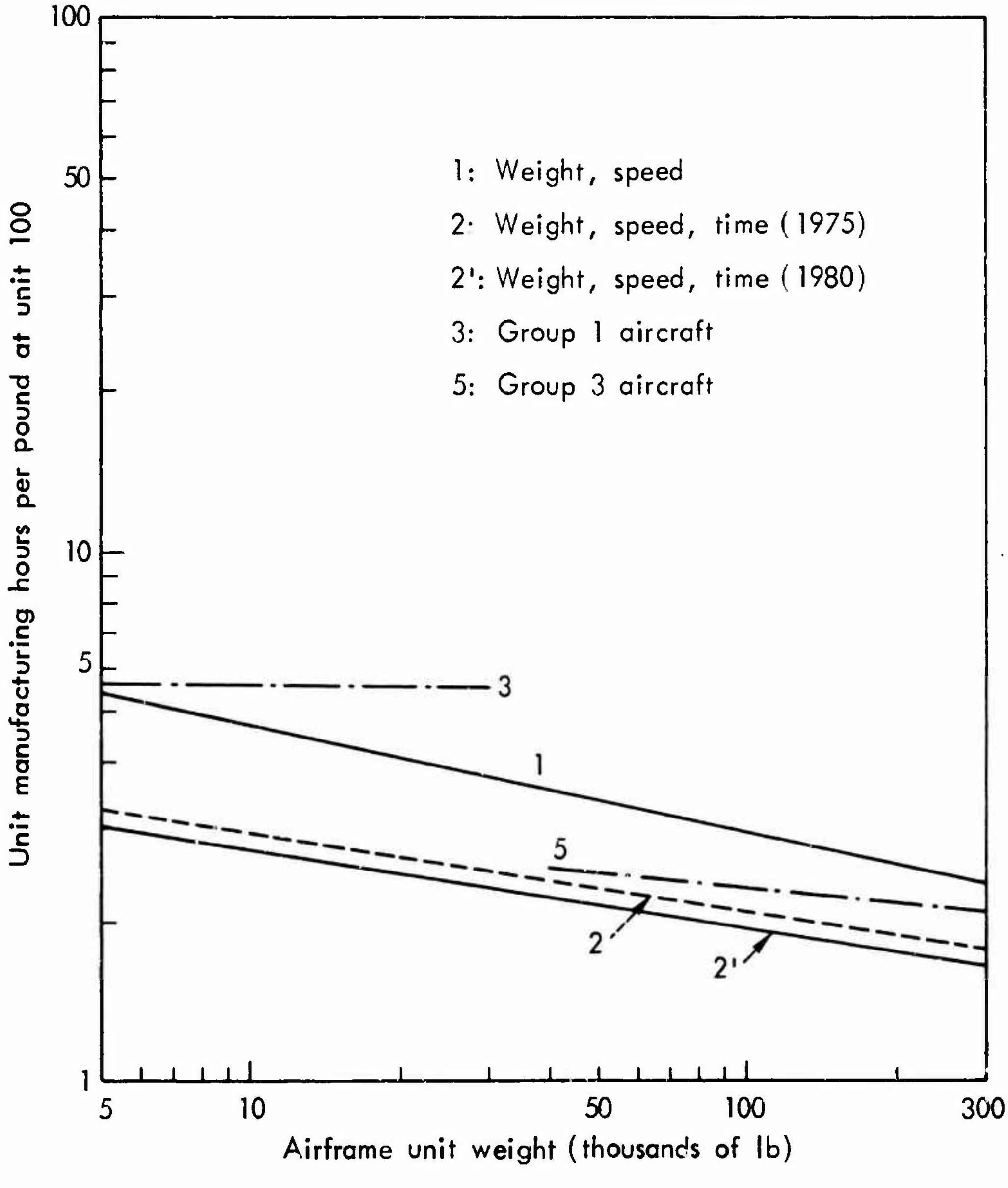

Fig. C-9—Unit recurring manufacturing hours per pound -- 550 kn

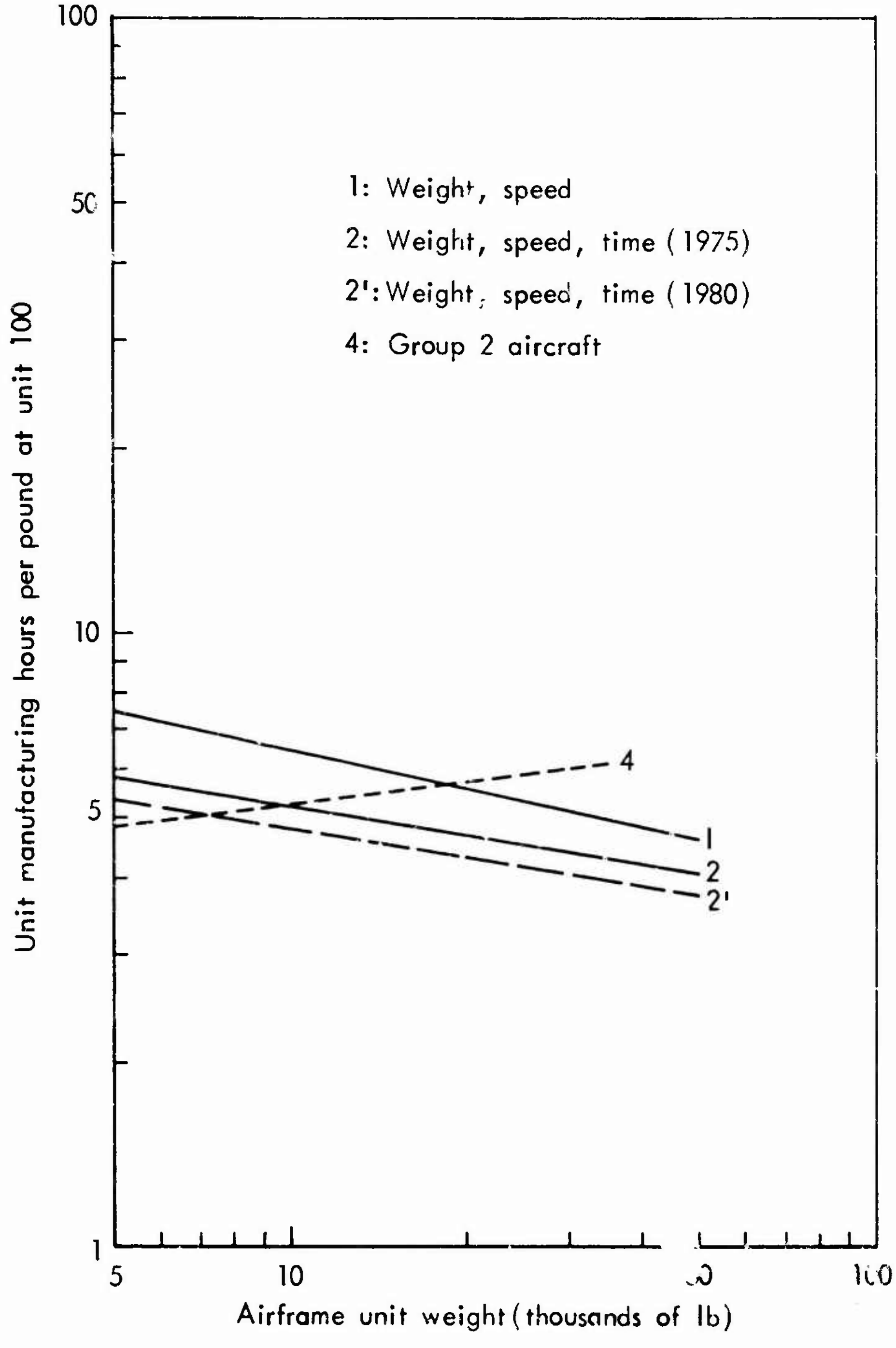

Fig. C-10 — Unit recurring manufacturing hours per pound -- 1150 kn

coefficient of the time variable (-.535) is such that a 7 percent decrease in hours is predicted between 1975 and 1980, and almost another 7 percent by 1985. Thus, in estimating manufacturing hours for future aircraft, one must ask whether reductions of that magnitude are consistent with investments in new capital equipment, developments in manufacturing techniques, new design practices, and new materials.

The decision on whether to use Eq. 1 (weight and speed) or Eq. 2 (weight, speed, and time) cannot be made without considering the implications for a closely related cost element, i.e., materials. If a time variable is used for estimating manufacturing hours, a time variable should be used for manufacturing materials as well. Reductions in labor over time tend to be offset by increases in materials cost. That relationship is discussed below.

MANUFACTURING MATERIALS COST

The materials estimating equations in the main body of this report were derived from 1973 costs. The constants below have been converted to 1975 dollars, using a composite index number of 1.273 derived by means of a procedure described in a previous Rand report.[4]

Nonrecurring Materials Cost

	Equation	Sample
1.	$MM_{NR} = .0306\ W^{.72} S^{1.02}$	24 aircraft--all types
2.	$MM_{NR} = .0802\ W^{1.30}$	Group 2
3.	$MM_{NR} = .658\ W^{.91}$	Group 3

where MM_{NR} = nonrecurring materials cost (thousands of 1975 dollars).

Figure C-11 shows four scaling curves for nonrecurring materials cost. (Group 1 is omitted because the regression equation had such poor statistical properties.) Again we have the characteristics displayed by Groups 2 and 3 in virtually all cost elements--a very steep slope for Group 2 aircraft and a lower cost for Group 3 because of their

[4] H. G. Campbell, *Aerospace Price Indexes*, The Rand Corporation, R-568-PR, December 1970.

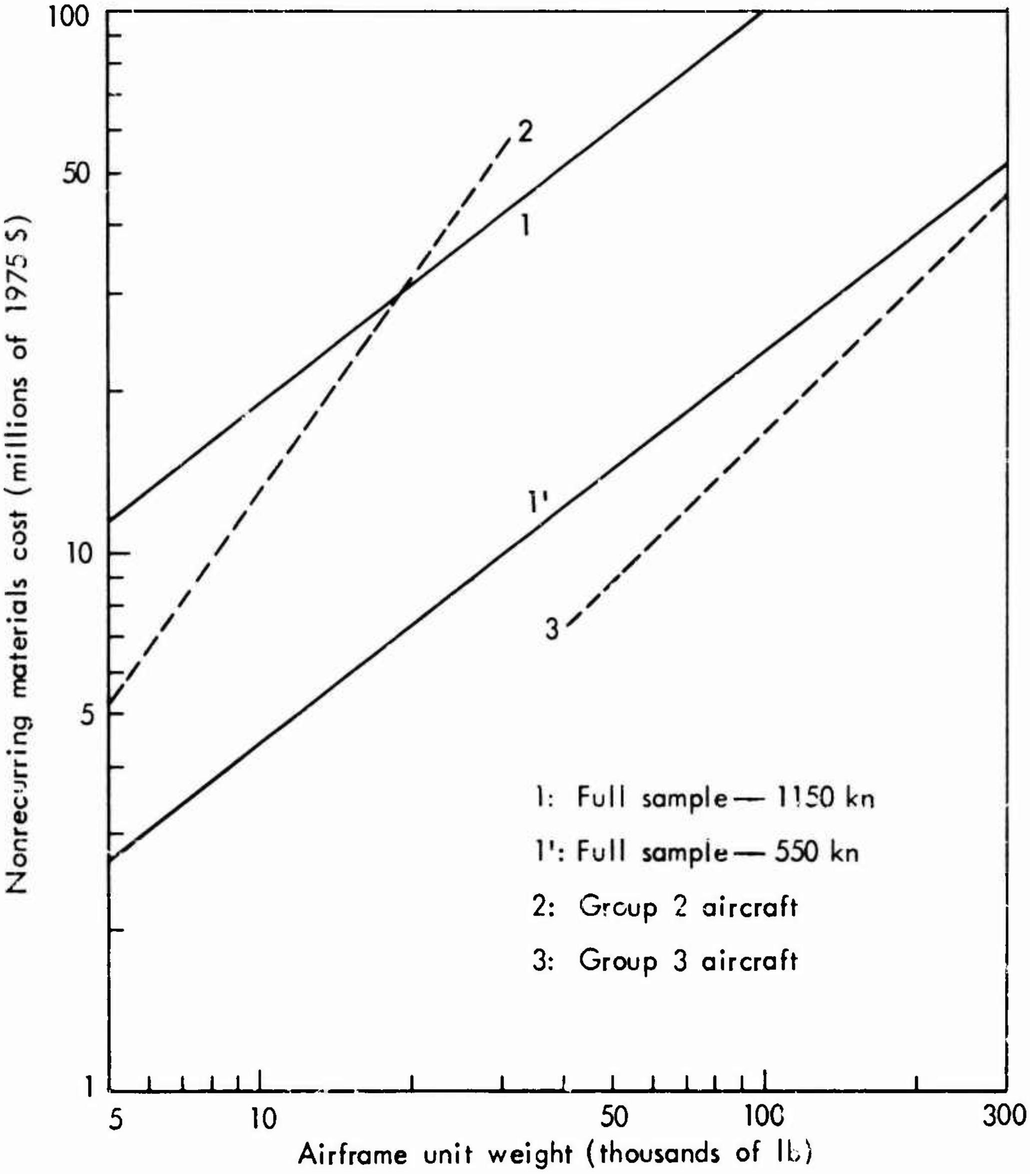

Fig. C-11 — Nonrecurring materials cost

lower speed. Equation 1 is clearly preferable because the slope is reasonable and the effect of different speeds can be taken into account.

Recurring Materials Cost

	Equation	Sample
1.	$MM_{100} = .0316\, W^{.833} S^{.751} T^{.465}$	24 aircraft--all types
2.	$MM_{100} = .0639\, W^{.880} S^{.867}$	24 aircraft--all types
3.	$MM_{100} = 1369\, W^{.406}$	Group 1
4.	$MM_{100} = .216\, W^{1.38}$	Group 2
5.	$MM_{100} = .101\, W^{1.30}$	Group 3

where MM_{100} = cumulative recurring materials cost at 100 units (thousands of 1975 dollars).

As in the case of manufacturing labor, two of the equations have almost identical statistical values but give very different estimates. Figures C-12 and C-13 show the difference in cumulative cost, and Figs. C-14 and C-15 in unit cost per pound. For a 50,000-lb airframe and a speed of 550 kn, Eq. 1 estimates a materials cost almost 40 percent higher than Eq. 2 when T = 1975 and 67 percent higher when T = 1980. The differences are not quite so great for higher-speed aircraft--28 percent for 1975 and 37 percent for 1980.

Theoretically, the idea of including a time variable is appealing because a trend to higher-cost materials has been apparent for some time. Practically, it is not clear that the use of a time variable (at least in the way it is used here) will improve estimating accuracy. A glance at the Y-deviations for the 10 most recent aircraft in the sample (Table C-2) does not show a pattern of increasing accuracy over time.

Nor is any other pattern apparent. Except for the A-6, the two equations underestimate the same aircraft and overestimate the same aircraft. Both underestimate very small aircraft (the T-38 and T-39) and very large aircraft (the C-5A). Both overestimate small aircraft (the A-7) and large aircraft (the C-141). Both overestimate and underestimate recent aircraft (the C-5 and F-14).

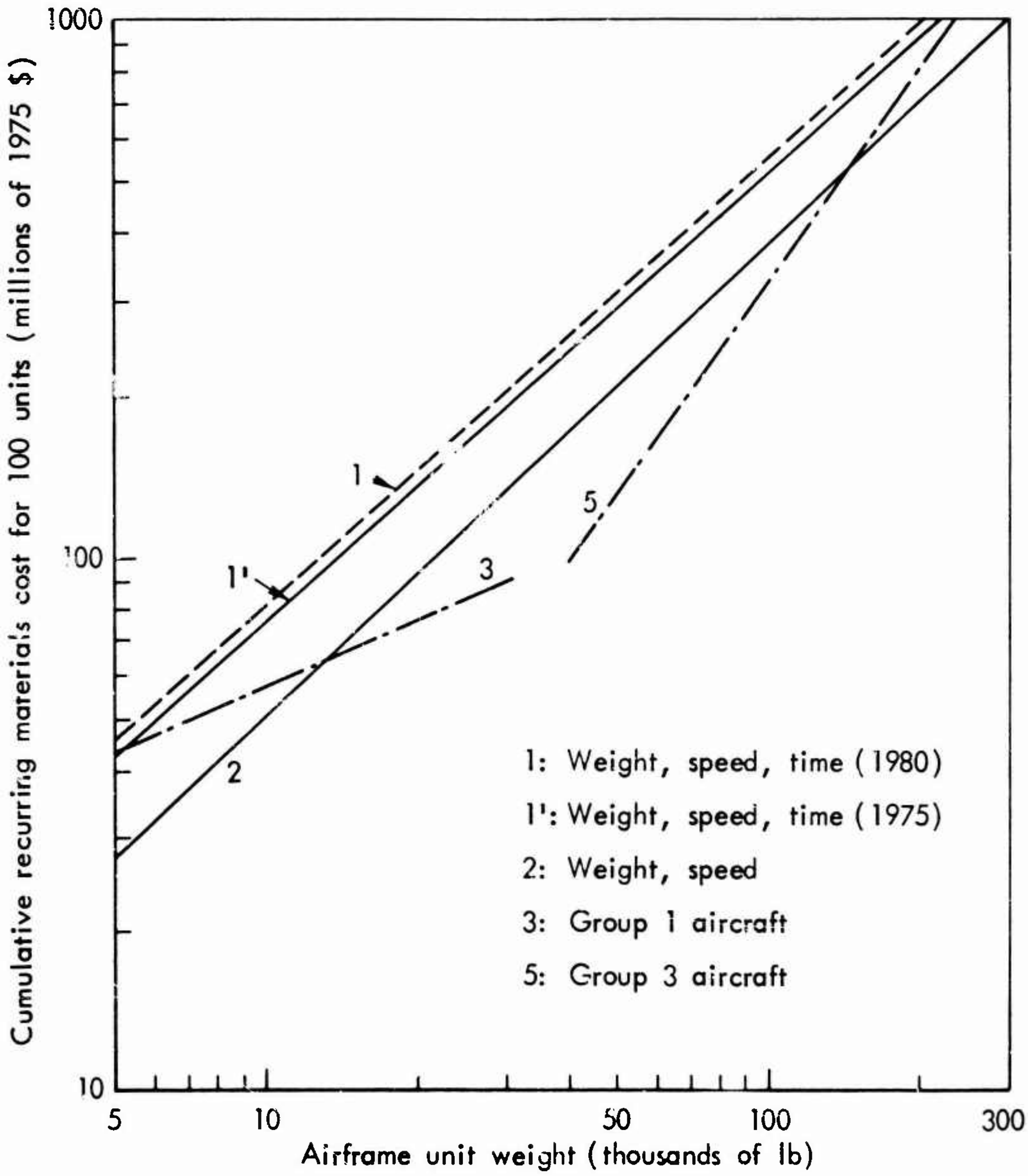

Fig. C-12—Cumulative recurring materials cost -- 550 kn

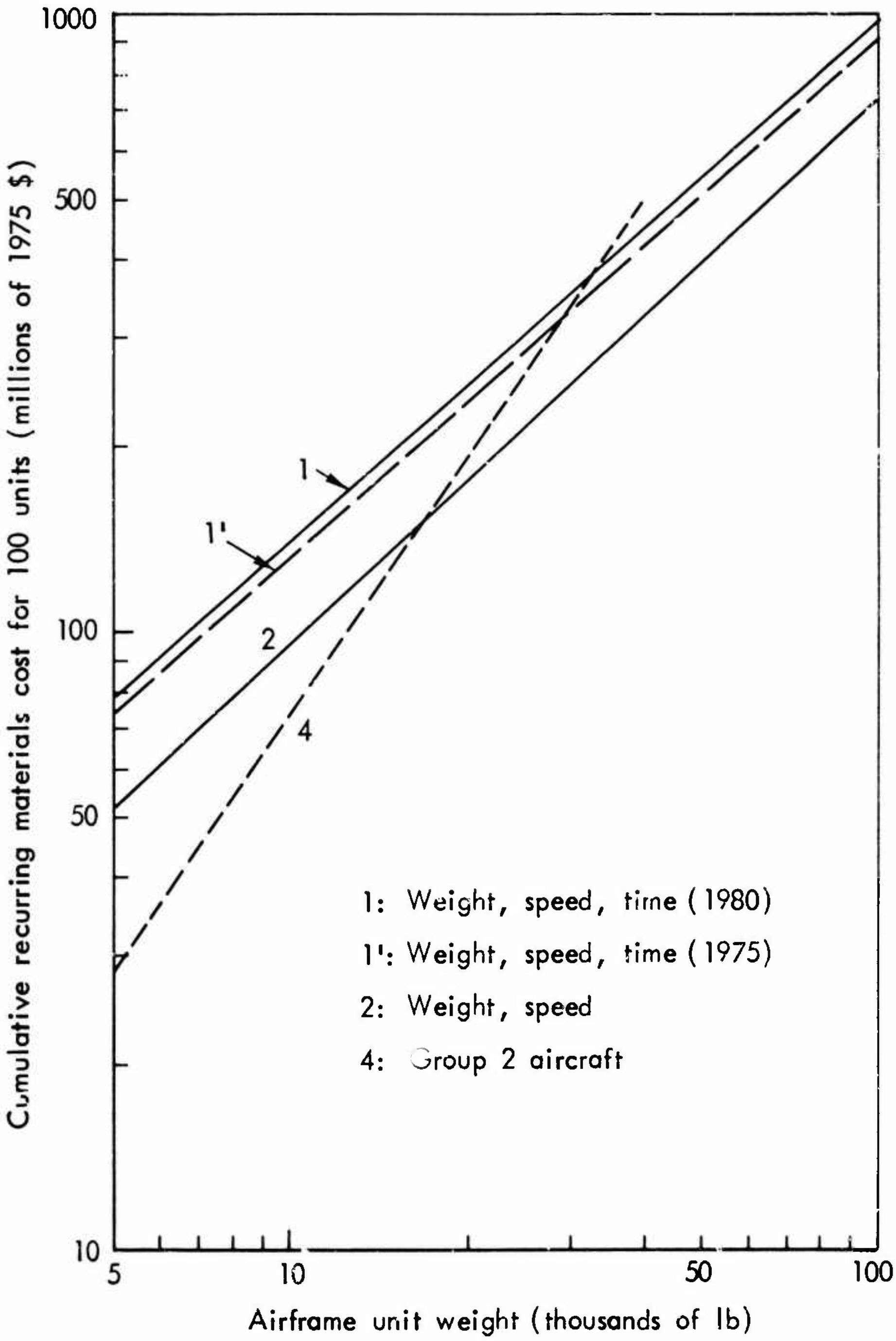

Fig. C-13 — Cumulative recurring materials cost -- 1150 kn

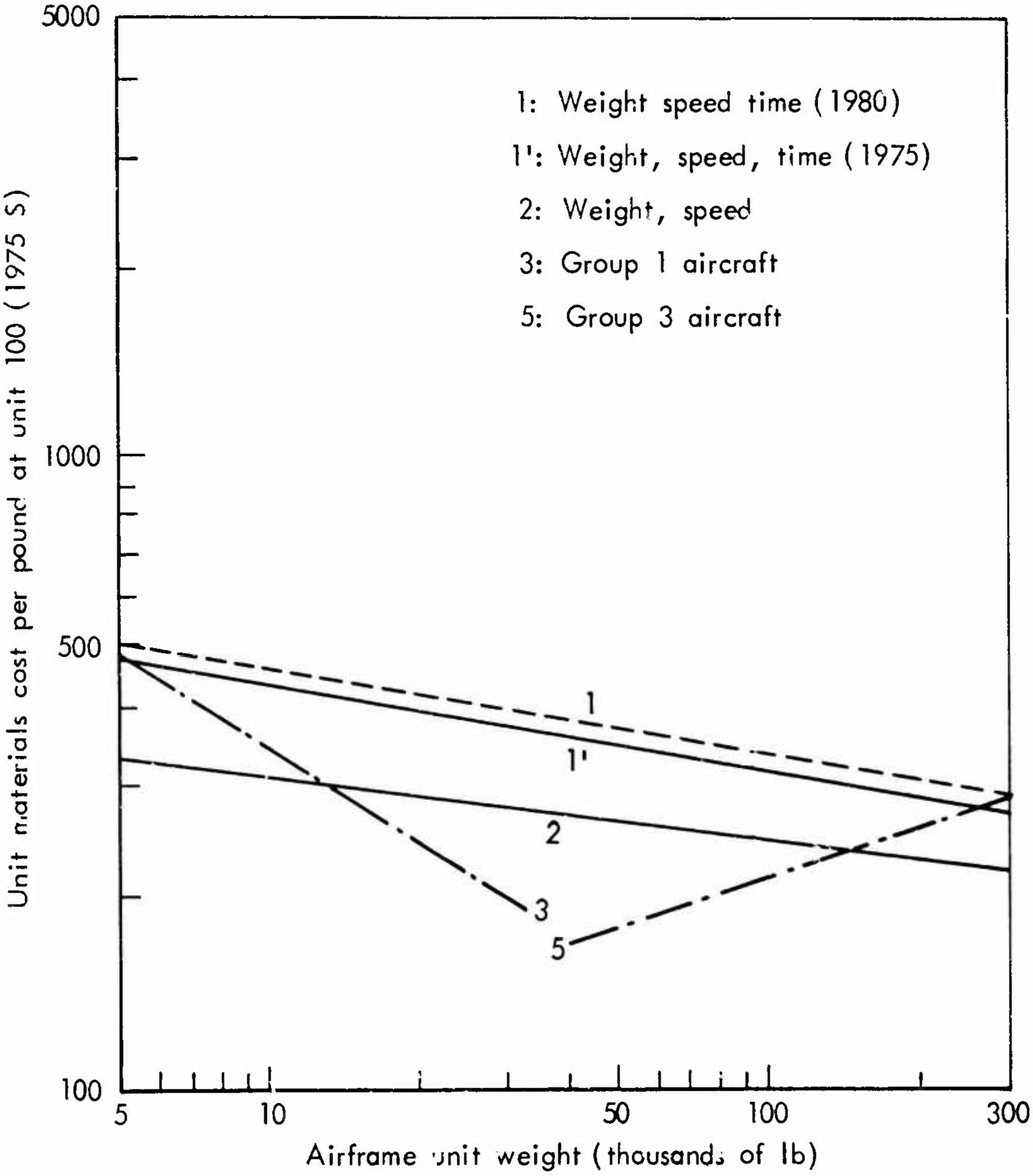

Fig. C-14--Unit materials cost per pound -- 550 kn

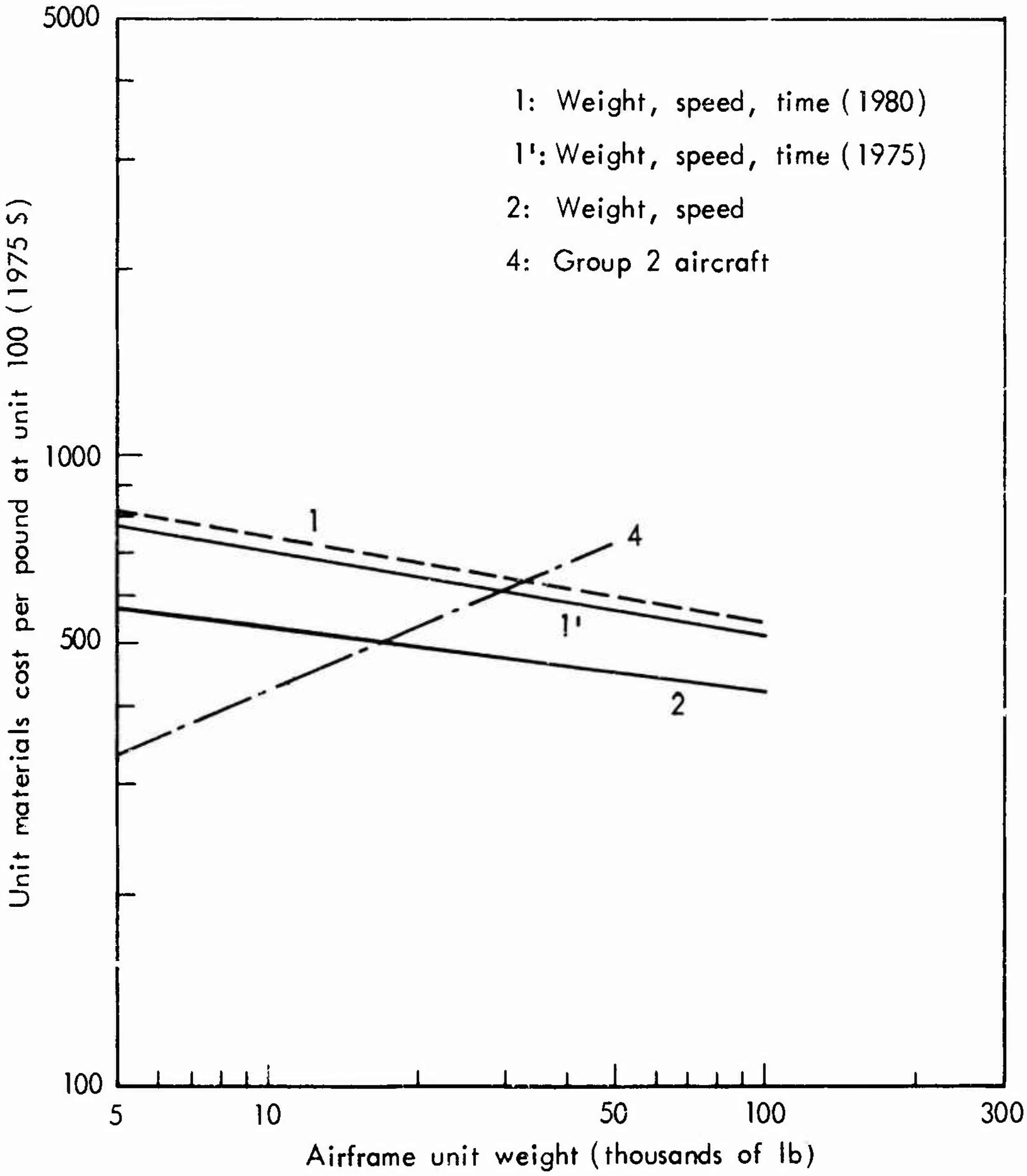

Fig. C-15 — Unit materials cost per pound -- 1150 kn

Table C-2

PERCENT OF Y-DEVIATION FOR MATERIALS COST

Aircraft	Weight, Speed	Weight, Speed, Time	Group 1, 2, or 3
A-5	2	6	-12
T-38	31	24	18
A-6	7	-4	19
T-39	22	7	22
F-4	15	15	21
C-141	-10	-24	-3
A-7	-7	-35	-6
F-111	20	9	1
C-5	39	28	14
F-14	-7	-30	-11
Absolute mean	16	18	13
Range	-10, +39	-35, +28	-12, +22

Since neither of the equations based on the full sample is really satisfactory, one may be tempted to consider the results obtained for the three subgroups. As shown by Table C-2, use of a more homogeneous sample does reduce the range of Y-deviations markedly. However, for Groups 2 and 3, the weight term has an exponent greater than one, and, as seen in Figs. C-14 and C-15, the effect is to increase cost per pound as airframe weight increases. This is contrary to experience, so we do not believe that the curves for Groups 2 and 3 represent actual trends. Problems with the data, and the influence of other variables such as time and speed, can give spurious results with such small samples.

Choice of the most appropriate estimating equation rests ultimately on judgment. One consideration, mentioned previously, is that internal consistency must be maintained in an overall airframe model. The same variables should be used for both manufacturing labor and manufacturing materials, i.e., either the time variable should be included for both or for neither. The reason, of course, is that materials increase in cost over time but labor hours are reduced; thus they tend to offset each other. One might assume that because of that balancing effect it makes little difference which pair of equations is chosen. However, a

comparison of combined estimates made for airframes of different sizes and speeds shows that including the time variable consistently gives results about 10 percent lower. Since experience teaches that the tendency over time has been to underestimate aircraft costs, the better choice on most occasions would be the equations that include only weight and speed.

FLIGHT TEST COST

The equation for flight test costs in Section VII has been adjusted by a factor of 1.177 to reflect the price-level increase since 1973:

	Equation	Sample
1.	$FT = .153\ W^{.71} S^{.59} N^{.72} DV^{-1.56}$	24 aircraft
2.	$FT = 3739\ N^{.76}$	Group 1
3.	$FT = .098\ W^{1.16} N^{.73}$	Group 2
4.	$FT = .76\ W^{.74} N^{1.0}$	Group 3

where FT = flight test cost (thousands of 1975 dollars),

N = number of flight test vehicles,

DV = dummy variable (2 for cargo aircraft; 1 for all others).

Figure C-16 shows three curves based on that equation when N = 5. It is perhaps surprising that the curve for cargo aircraft is so much lower than the curve for other military aircraft at the same speed. Our data show, however, that flight test costs for the C-130, C-133, KC-135, C-141, and C-5 are substantially lower, when compared on a normalized basis, than the costs of the B-52 or the fighter-bombers. Typically, flight test costs for cargo aircraft are less than 2.5 percent of total program cost for 100 aircraft, compared with 5 to 6 percent for other aircraft. Mach 2 aircraft, as shown by curve 1, are distinctly more expensive to test--their flight test costs are about 6 to 8 percent of total program cost for 100 aircraft.

TOTAL COST

It can be argued that inconsistencies in defining and accumulating data for the individual cost elements make those data suspect, while

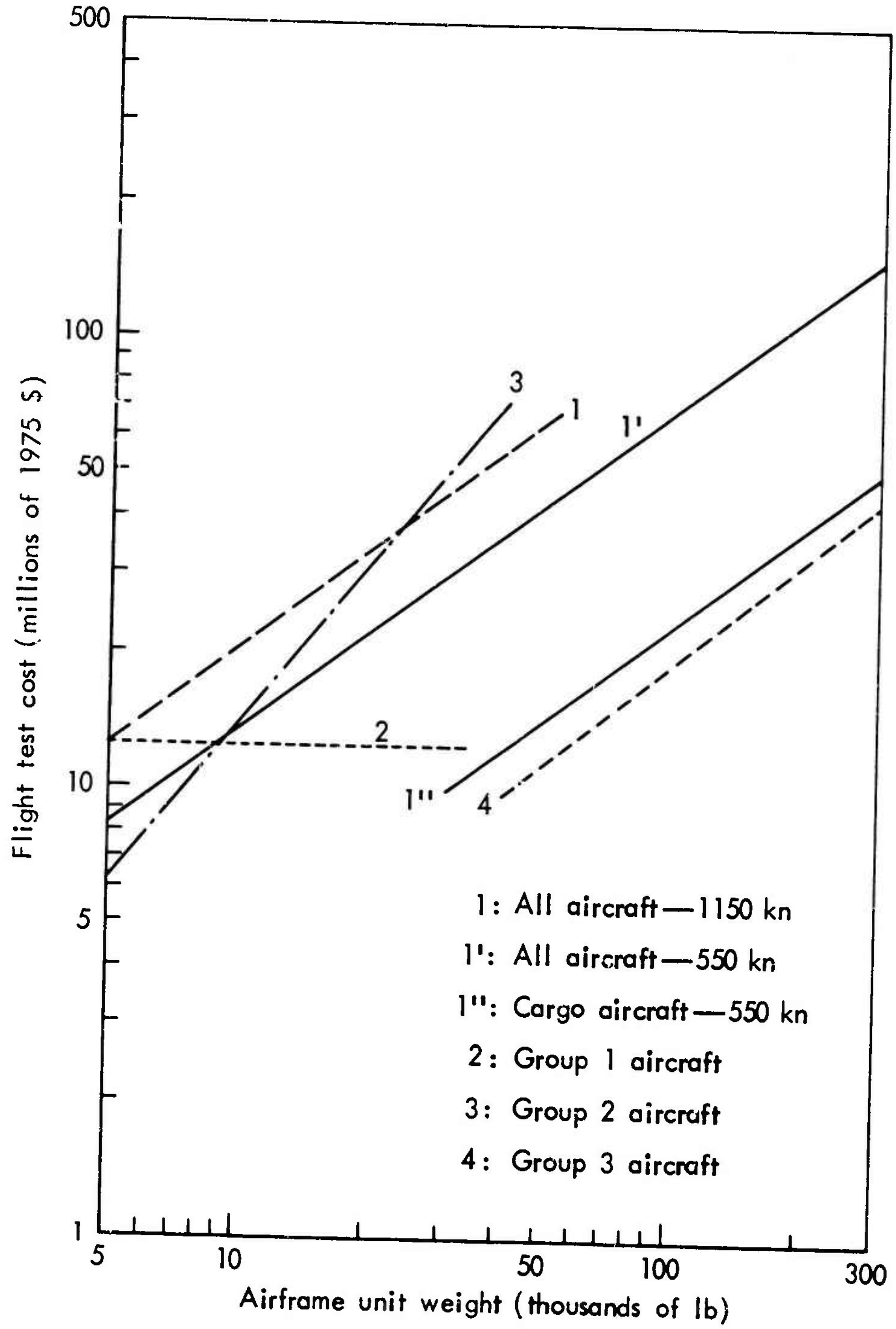

Fig. C-16—Flight test cost (5 test aircraft)

total cost is a known quantity. In dealing with total airframe cost, the analyst does not have to make arbitrary allocations among elements, convert outside production costs to direct labor and materials costs, worry about whether Other Direct Charges are treated consistently, etc. Thus, estimates of total cost should be more accurate than those of any cost element.

The problem from a procedural point of view, however, is to obtain total costs that are comparable for aircraft built at different times and by different contractors. Common wage rates and overhead rates must be assumed, and all costs must be adjusted to a common year. Thus the total cost used for analytical purposes is not the total cost of record and is a function of the rates chosen. To convert hours to dollars and arrive at a cost for each cost element, we used the composite hourly rates shown in Table C-3. They are based on rates quoted to Rand by several airframe manufacturers in mid-1975 and may or may not be representative of the industry as a whole. They include labor, burden, G&A, miscellaneous direct charges, and, in the case of tooling, materials. Actually, rates change throughout a program as the mix of senior and junior, skilled and semiskilled workers changes, but we have assumed a constant rate during development and a constant rate during production.

Table C-3

COMPOSITE HOURLY RATES

Cost Element	Development ($)	Production ($)
Engineering	26.50	21.75
Tooling	24.25	22.75
Manufacturing	23.75	22.00
Quality Control	24.50	23.00

The rates shown in Table C-3 are considerably higher than those given in Section IX for 1973, and a major disadvantage in dealing in total cost is the need to adjust the estimating model every year for rate and price changes. We developed an overall adjustment factor of 1.28 by examining the change in each cost element separately, and incorporated that factor in the total cost equations:

	Equation	Sample
1.	$TC_{100} = 5.49\ W^{.73} S^{.74}$	24 aircraft--all types
2.	$TC_{100} = 2697\ W^{.58}$	Group 1
3.	$TC_{100} = 13.35\ W^{1.16}$	Group 2
4.	$TC_{100} = 30.92\ W^{.96}$	Group 3

where TC_{100} = total cost for 100 units (thousands of 1975 dollars).

Figure C-17 shows two curves based on the total cost equation and curves for each of the three aircraft subgroups. Again Group 2 has a very steep slope, which makes small high-performance aircraft very cheap and large high-performance aircraft very expensive. It depicts the costs of Group 2 aircraft fairly well, but it is unsuitable for estimating beyond the limits of the sample. Group 3 aircraft are again generally below the total sample, but the high cost of the C-5A relative to other cargo aircraft influences the curve so that it intersects the total-sample curve at about 300,000 lb.

The results obtained by using a data sample of total costs differ very little from those obtained by summing the estimates of the individual cost elements. Figure C-18 shows total cost curves based on such summations.[5] Individual aircraft costs shown for reference purposes, it must be remembered, are not the actual costs incurred by manufacturers.

The fact that estimates based on total cost are no better than those based on a summation of estimates of each cost element is not surprising. It has been suggested, however, that total-cost estimates are more reliable than estimates of the individual elements because of complementarities. For example, a lower-than-average cost for manufacturing labor may be offset by a higher-than-average cost for manufacturing materials, etc. To test that hypothesis, we computed the percentage of error contributed by each cost element for all aircraft in the sample. We estimated each cost element separately, using the equation described

[5] Equations based on the full sample of 24 aircraft were used to estimate all individual cost elements except engineering. For engineering, we used the full sample only for aircraft developed prior to 1958. Estimates of more recent aircraft were made using the equation based on a sample of 9 newer aircraft of all types.

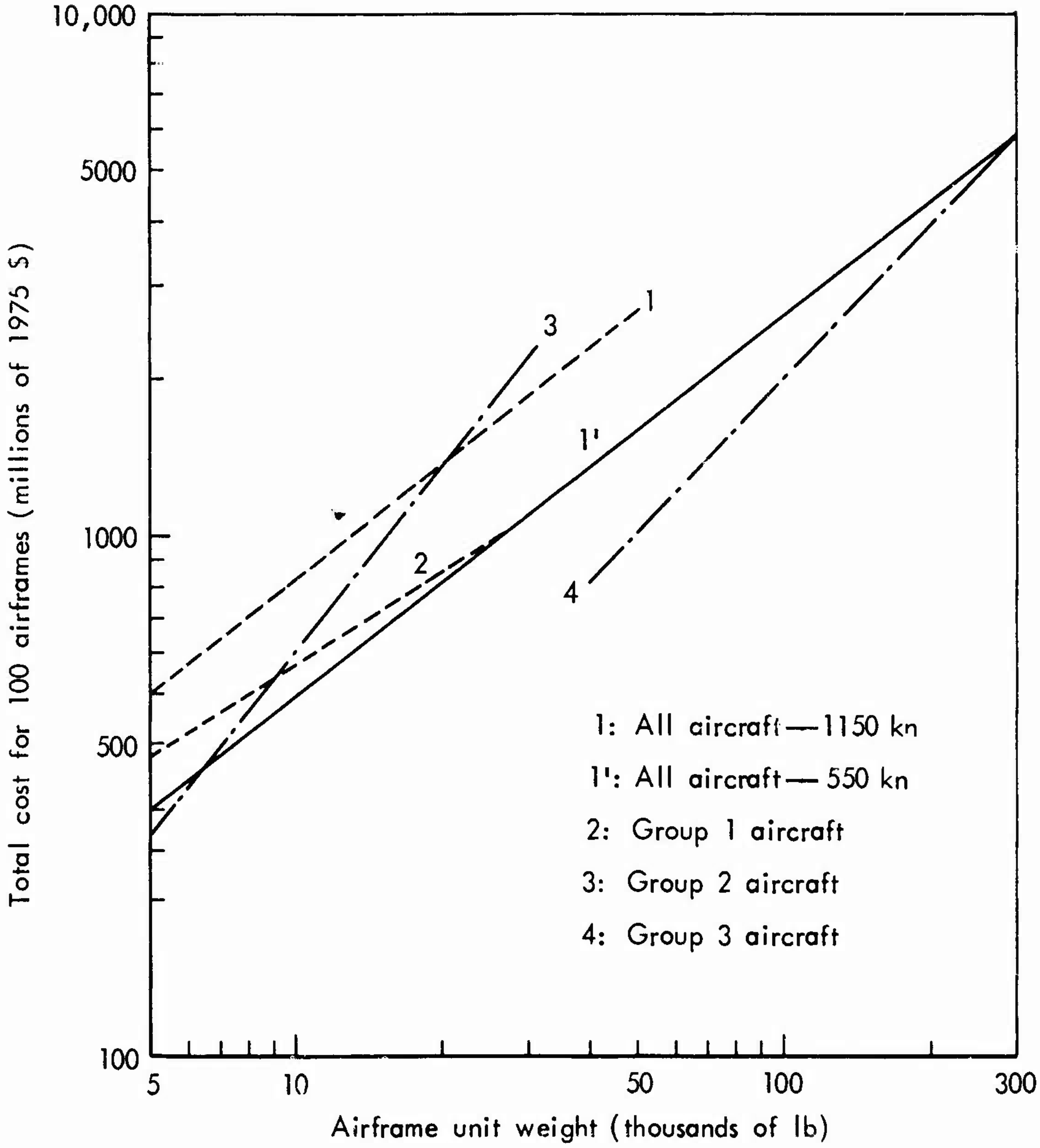

Fig. C-17—Total airframe cost (100 units)

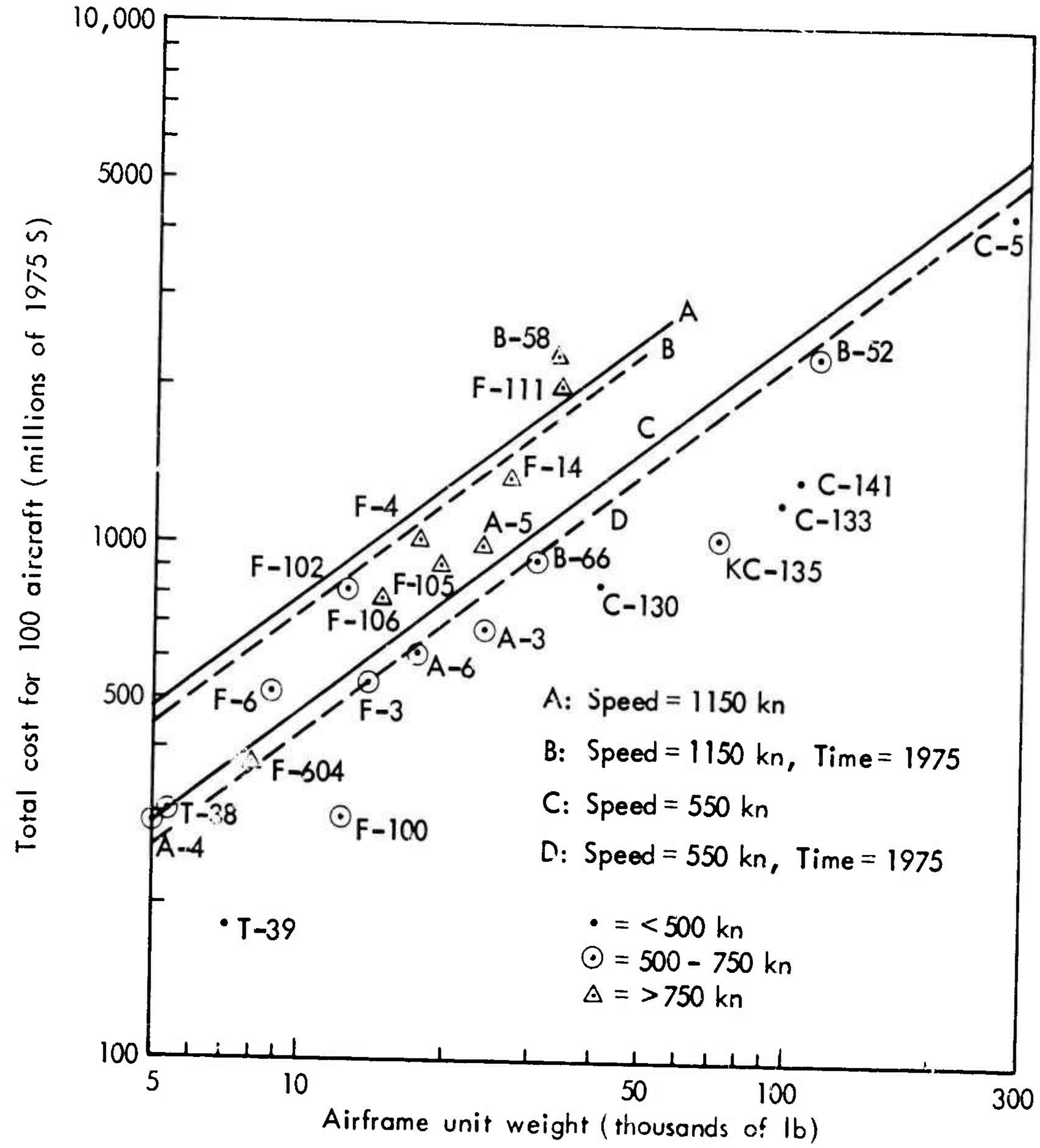

Fig. C-18—Total airframe cost (100 units) based on summation of cost elements

in footnote 5 and, where necessary, converted to 1975 dollars. Table C-4 shows the percentages obtained. It appears that in 17 out of 24 cases, the sum of the errors is larger than any individual error. No obvious complementarities are apparent between engineering and manufacturing labor, manufacturing labor and materials, or tooling and manufacturing labor. In 6 of the 24 cases, all elements have the same sign. Thus, while complementarities undoubtedly exist in individual cases, no pattern could be detected. What is clear is that manufacturing labor is the greatest source of error, which is to be expected because it is the most important cost element.

Table C-5 shows the percentage of total cost at unit 100 incurred by each of the four major cost elements. We thought that certain systematic variations among percentages might occur, e.g., high-performance aircraft might have a higher percentage of cost devoted to engineering and large aircraft might have a higher percentage devoted to materials. However, as Table C-5 makes evident, much of the variation is random. Mach 2 aircraft tend to be above the mean in engineering and materials and below the mean in manufacturing labor, but there are always exceptions. Large aircraft are close to or below the mean in engineering, close to the mean in labor, and above the mean in materials. No general observation about tooling is possible except that the high-performance aircraft tend to be at the low end of the range.

What Table C-5 shows most forceably is the importance of manufacturing labor relative to the other cost elements, and it becomes increasingly important during the course of a production program as fewer engineering and tooling hours are incurred. Figure C-19 shows how the percentage of total cost devoted to each cost element changes as more aircraft are produced. (The percentages were computed assuming a 30,000-lb, 1150-kn aircraft with a 20-aircraft flight test program.)

A good estimate of manufacturing labor reduces the possible margin of error for an estimate of total cost. Parametric equations such as those discussed here provide a good basis for an estimate, but when other relevant information is available, it should be taken into consideration. Since both industry and DoD agencies have long concentrated on manufacturing-hours-per-pound curves, there is more historical

Table C-4

PERCENTAGE OF ERROR CONTRIBUTED BY MAJOR COST ELEMENTS

Aircraft	Engineering	Tooling	Manufacturing Labor	Manufacturing Materials	Total
A-3	-13	0	4	0	-9
A-4	-6	11	7	4	16
A-5	-8	-7	-8	1	-22
A-6	0	-5	10	[illegible]	6
B-52	-3	4	-12	7	-4
B-58	6	9	5	8	28
RB-66	-11	13	7	-3	6
C-5	4	0	3	8	15
C-130	9	2	-5	5	11
C-133	1	-2	-4	-2	-7
KC-135	-10	5	-26	-6	-37
C-141	-7	-8	-16	-2	-33
F-3	-7	-1	0	0	-8
F-4	-5	0	4	3	2
F-6	-6	6	18	2	20
F-14	-1	-3	1	-3	-6
F-100	-8	-13	-35	-6	-62
F-102	2	10	15	4	31
F-104	-16	-2	-21	-4	-43
F-105	-2	-6	4	-6	-10
F-106	-7	3	-7	4	-7
F-111	3	2	6	5	16
T-38	5	4	-9	5	5
T-39	-6	-9	-5	1	-19
Absolute mean	6	5	10	4	18

information on manufacturing labor than on any other cost element. The wealth of hours-per-pound data that is easily available, plus a knowledge of any special fabrication and/or assembly techniques to be used by a particular company on a particular aircraft, should enable an estimator to make a valid prediction of manufacturing hours prior to the time an aircraft is produced. The other cost elements present a greater problem because they are not so readily expressed in hours or dollars per pound, and less data are available. However, if the level of accuracy shown in Table C-4 can be obtained by using a parametric model, the estimate of total cost should be within the bounds of acceptable accuracy.

Table C-5

PERCENTAGE OF TOTAL COST INCURRED BY INDIVIDUAL COST ELEMENTS

Engineering

%	Aircraft
8	RB-66
9	A-3
12	B-52, KC-135, F-102
13	C-133, F-6, T-39
14	A-4
15	F-3, F-106
19	C-5, C-130, C-141
20	A-6
21	F-4, F-100
22	B-58, F-105
23	A-5, F-104, F-111
28	F-14
31	T-38
18	Mean

Tooling

%	Aircraft
12	A-5, F-105
13	A-6, C-5, F-14
14	F-111
15	C-141, F-4
17	C-133
18	F-3
19	A-3, B-52, B-58, F-100
20	C-130, F-6, F-106, T-39
22	F-102
23	F-104, T-38
27	A-4
29	RB-66, KC-135
19	Mean

Manufacturing Labor

%	Aircraft
22	T-38
28	F-104
29	B-58
30	F-106, F-111
31	F-14
34	A-5
36	B-52, F-4
37	F-100, A-4
38	C-5, F-102
39	C-141, KC-135, C-130
40	T-39
42	F-3
43	A-6
46	F-6
47	F-105
48	RB-66
51	A-3
52	C-133
38	Mean

Manufacturing Materials

%	Aircraft
7	RB-66
10	F-6, F-105
11	C-133, F-3, F-102
12	A-3, A-4
13	A-6, F-100
14	KC-135, F-104
16	C-130, T-38
17	F-4, F-14
18	B-58, F-106, T-39
19	A-5, F-111
20	B-52
22	C-141
25	C-5
15	Mean

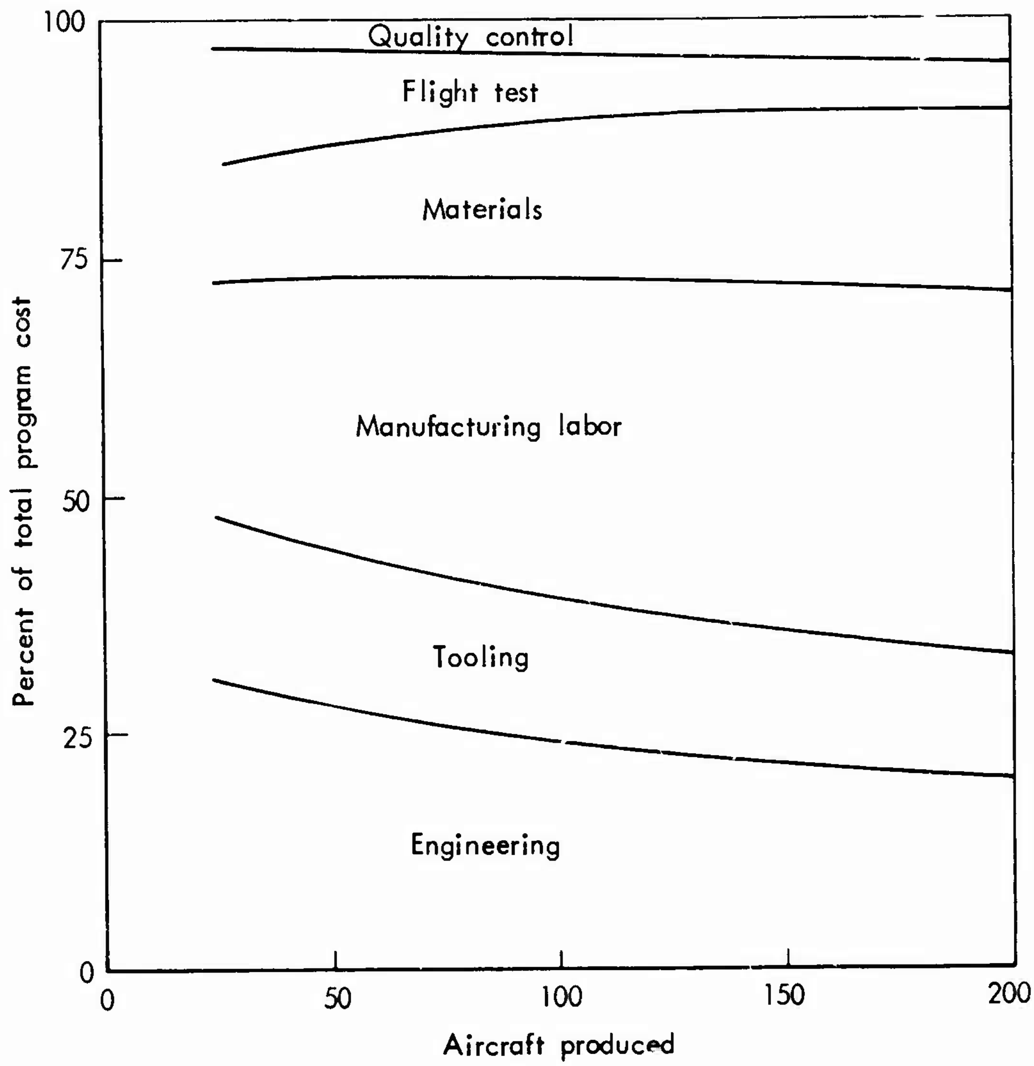

Fig. C-19 — Percentage of cost devoted to major cost elements

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A set of generalized equations for estimating development and production costs of aircraft airframes on the basis of such characteristics as aircraft weight and speed. (Extensive investigation has shown that these characteristics explain cost variations better than any other objective parameters.) Equations derived by multiple-regression techniques are presented for each of the major cost elements, for total program cost, and for prototype development costs. The report explains the derivation of each equation and describes the treatment of the data, the fitting of regression equations, and selection of preferred equations. A detailed numerical example is included which applies to preferred equations and compares the results to those obtained using several sets of alternative equations. (JMD)